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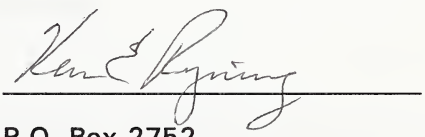
(signed) 

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Department of Rural Economy for acceptance, a project paper entitled Stochastic Dominance Analysis Using a Biophysically Modelled Crop Production Function submitted by Ken Ryning in partial fulfillment of the requirements for the degree of Master of Agriculture.

Dr. L. Bauer (Supervisor)

Dr. F.S. Novak

Dr. R.F. Grant

Date: 26 February, 1993

UNIVERSITY OF ALBERTA

STOCHASTIC DOMINANCE ANALYSIS USING A BIOPHYSICALLY MODELLED CROP PRODUCTION FUNCTION

BY

Kenneth Earl Ryning

A project paper submitted to the Department of Rural Economy in partial fulfillment of the requirements for the degree of

MASTER OF AGRICULTURE

DEPARTMENT OF RURAL ECONOMY

Edmonton, Alberta

SPRING 1993

UNIVERSITY OF ALBERTA

DEPARTMENT OF RURAL ECONOMY

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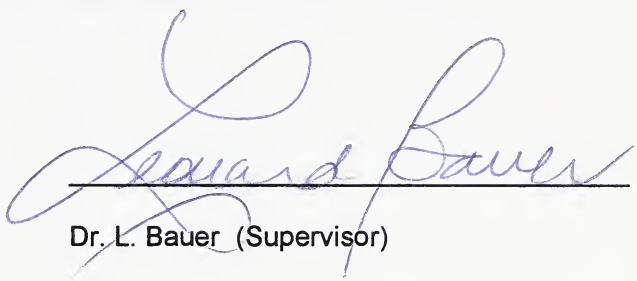

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This work is dedicated to the glory of God

ABSTRACT

This project paper attempted to combine the disciplines of agronomy and economics via the exploration of biophysical and bioeconomic crop production simulation models. The economic problem to be solved was the determination of the best combination of applied nitrogen fertilizer rates given the unpredictable nature of soil moisture and seasonal precipitation in the production of hard red spring wheat (*Triticum aestivum* L.). A complete factorial design of ten incremental nitrogen and available spring soil moisture levels were input along with daily weather, soil profile, and cultural practices data into the CERES-Wheat (v2.10) crop growth simulation model. Ordinary least squares regression was used to specify quadratic and square root production functions with nitrogen rates and total available moisture being the independent variables of the dependent variable yield. These functional forms proved to be comparable in fit (R^2 = 0.68 to 0.70) to empirically derived yield functions found in the literature. Second degree stochastic dominance analysis using an expanded Lotus 1-2-3 spreadsheet model (STOCHAST.wk1), capable of handling 125 fertilizer application strategies, gave results which suggested a range of total nitrogen rates in the order of 122 - 158 kg ha^{-1} over poor, good, and excellent available spring soil moisture regimes. Risk adverse producers of wheat in the central Alberta black soil zones would be advised to consider these total nitrogen rates to optimize gross margin returns over the long run providing weather patterns remain the same as they have for the past 30 years.

Keywords: Bio-physical, bio-economic, production function, CERES-Wheat, nitrogen response, moisture, stochastic dominance.

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Ken Ryning, P.Ag

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I.) INTRODUCTION

Throughout this past century, crop response to applied nitrogen fertilizer and available soil and atmospheric water has been the subject of much study. Crop producers have witnessed the well documented yield responses for the many crop types investigated by agronomists. Economists have analyzed this empirical data to suggest inputs of both fertilizer and irrigation water that would maximize profits. Soil testing laboratories have incorporated these response functions into their fertilizer recommendations to crop producers. Whether or not actual applications are made according to these recommendations is a matter of confidence in the reliability of the response functions to an individual's farming operation. The probability of water being available for crop growth plays a large part in a decision maker's application of nitrogen fertilizer. Since soil types and moisture distribution patterns vary greatly across broad agroclimatic regions and soil zones it would be more beneficial for farmers to have localized data from which to make decisions on applied fertilizer nitrogen. It is an objective of this paper to reproduce a localized wheat yield response to applied fertilizer nitrogen and available soil moisture.

The necessary field research to obtain such data can only be carried out in a few areas of the prairies largely due to prohibitive costs and lack of trained manpower. It is postulated that computerized, crop growth simulation models would be able to generate the necessary long term data for the estimation of yield response functions. Furthermore a stochastic dominance model incorporating the functions and probabilities derived from such data would be valuable in aiding the decision making process regarding spring fertilizer application. Why do we build models? Models simulate real life processes and can be used as predictive tools (Klein, 1981). To make the best forecasts of

future life processes or behaviours an accurate description and representation of past events is necessary. Mathematical computer models that simulate both past events and future likelihoods are valuable tools in our understanding of crop responses to the environment and in how best to manipulate that environment for satisfaction of the crop producer's utility. Models as discussed in this paper are representations of agricultural systems with a simplified approximation of reality. Simulation models, as described by Nadler, capture the essence of reality but do not duplicate exact reality. Models serve as a means of better understanding the structure and extent of the systems that they describe or emulate.

Stokey and Zeckhauser (1978) describe a progression of dynamic model types. They start with the physical model as a scaled up or a scaled down version of the real thing as witnessed in the recent farm toy craze or classroom models of DNA molecules. These have limited use in that once they are built they are static and inactive. Changes are harder to make to them. The structure is evident but their true interactive nature is concealed or underrepresented. Another type of model is the map or the blueprint to represent what has been laid out already, such as country roads or geophysical land forms, or could be built up from scratch, such as an high rise office tower or jet liner. Changes are more easily made to the later of these two representations of reality before the object takes form. Planning decisions can be made more readily with an accurate map (model) depicting the surrounding features of the country side. A third model type that attempts to describe functional reality takes the form of diagrams, flow charts, decision trees, charts or graphs. These explain the relationship between component parts of the system. Some of the dynamics of

the system can be felt as one works through and understands the mechanisms of the system that are modelled.

Mathematical models represent a more dynamic look at a real phenomenon. The equations upon which these types of models are constructed are easily manipulated or fed new inputs especially with today's computer capabilities. If the equations and input parameters are truly representative of reality, fairly accurate portrayals of a functioning system can be simulated. Model accuracy relies on reduction of human, plant, and animal behaviours to comprehensible mathematical constructs.

OBJECTIVES OF THE STUDY AND ORGANIZATION OF THE PAPER

The Objectives of this M. Ag. project paper are threefold:

1. To use an existing crop yield simulator CERES-Wheat (Godwin et al, 1990) and determine wheat yields with 30 years of historic weather data from the Edmonton International Airport and local soils data from the University of Alberta research farm at nearby Ellerslie. Progressively increasing nitrogen fertilizer and available soil moisture regimes were used to simulate yields.

2. To calculate a simple linear production function for the growth of wheat using the data obtained in #1 above, that can be used for economic analysis. (i.e., the determination of optimal variable inputs for the most economical output of wheat)

3. To expand upon a discrete stochastic dominance model for fertilizer application strategies using varying levels of initial spring soil moisture combined with total growing season precipitation. The economic decision

rule to be used here is one by which second degree stochastic dominance criteria will satisfy risk adverse behaviour concerning fertilizer costs and applications, and the best possible expected net value over the long term.

The paper is organized into seven main sections. The first is a general introduction to modelling followed by a literature review in the areas of biophysical crop modelling in relation to economics, bioeconomic crop modelling and the formulation of a production function, and lastly wheat and barley responses to water and nitrogen. The third section briefly puts forward an understanding of wheat growth in the realm of growth models and gives an explanation of the CERES-Wheat dynamic simulation model used in this study for the generation of yield data. Initialization, calibration and validation sequences of this biophysical model are outlined in this section. Input and output data from the model are noted with details included in the appendix.

Using the data collected for and generated from the biophysical model, the criteria by which the production function was chosen are explained in the fourth section. The fifth section outlines the theory of stochastic dominance and includes an explanation of an interactive, dynamic Lotus 1-2-3 spreadsheet model. This is made available for use by the reader to observe the graphic nature of means and variances based on the production function calculated in the fourth section. First and second degree stochastic dominance criteria are applied to 125 strategies of fertilizer application in this spreadsheet. Efficient strategies are calculated, sorted and can be graphically analyzed. Results and discussions of the findings are included in the sixth section, while the last section offers a summary and conclusions.

II.) LITERATURE REVIEW

A. BIOPHYSICAL CROP MODELLING

Biophysical simulators of which crop growth models are a part are "complex mathematical models of some process with explicit attention to biological and physical determinants of agricultural production." (Musser and Tews, 1984) They are a subset of the process oriented models along with Bioeconomic simulators discussed in the next section. The biophysical simulators came into prominence in the late nineteen seventies and early nineteen eighties; chiefly from the southern U. S. A. in centers of biophysical simulation development such as Mississippi State, Oklahoma State, and Texas A & M. Universities. They have been used in the irrigation sector extensively to determine optimal water application strategies for row crops such as corn (*Zea maize*) and soybeans (*Glycine max*), and in fertilization studies on wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), rice (*Oryza sativa*), forages and tree fruits. Hog and beef cattle production has also been simulated. Other agricultural systems that have been successfully modeled and which impinge on the biological side are the soil conservation and management strategies of this past decade, development of machinery sizing and efficiency simulators, Integrated Pest Management schemes, and grain drying and storage systems.

Crop models provide an alternative means of representing the production function. They have wider usage in the long run to answer questions by a number of different disciplines. Environmental input especially, can serve as more than the single purposed variable of the production function thus broadening the scope. "Capacity can be built into the simulation model to allow evaluation of a wider range of environmental conditions than would normally be experienced under typical field based environmental conditions." (Musser and

Tews, 1984) This is especially true if it is dynamic or can build in the passage of time. The daily incrementing models such as CERES have the potential to link several years of weather data and look at long term response trends to management. If the mechanisms for environmental crop response could be encoded in these dynamic mathematical models with the assurance of a reliable response to the dynamic and stochastic changes in the environment, then the intersite applicability of the empirical biophysical researchers' findings could be much more widely used and less restricted to the research location. (Talpaz and Mjelde, 1988; Mapp and Eidman, 1975; Vaux and Pruitt, 1983) Models are also used to avoid expensive, time consuming field trials at specific locations, however, the field work is still necessary for the collection of the basic data to build the simulation models. When these advanced models are used as the "blueprints" for agricultural systems they could help reduce costs associated with the subsequent development of such projects as irrigation strategies, the use of irrigation water and capital; resulting in subsequent increased net return to the farmer. (Mapp and Eidman, 1975)

These modelling developments have not been without their difficulties, key to which is the interdisciplinary cooperation and ample resources needed in the planning and implementation of these simulators. Griffen (*et al,* 1985) stated that the data intensive nature of the models had been a weakness along with the often times poorly validated biological and physical relationships amongst the dependent and independent variables of production function based models in the scheduling of irrigation inputs. Typically all that could be done after such an exercise was to extract basic economic data using traditional static tools of analysis and provide more experimental data for the biophysical researchers. A case study was done by Dillon (*et al*, 1989) where four biophysical simulation

models (CORNF, SORGF, TAMW, & COTTAM) were used to simulate yields under incremental production practices of date of seeding, population density, and maturity class differences over 37 years of weather data. Output results herein were not validated by actual field data but were generally confirmed by consulted agronomists. Quadratic programming to economically optimize an objective function of expected profit maximization tied the bioeconomic nature of present day models to these biophysical models developed in the early nineteen eighties.

B. BIOECONOMIC CROP MODELLING AND FORMULATION OF THE PRODUCTION FUNCTION

Functional forms are the next step in integrating the disciplines of the environmental sciences with those of the economic community. "It is impossible to determine which functional form more closely approximates the 'true' functional relationship, since the true relationship is unknown." (Griffen *et al,* 1987). The production function is therefore only our best approximation based on the hypothesis that we have about the input-output relationships of our models. As well statistical estimation can be complicated by multicollinearity, excess parameters to measure, loss of degrees of freedom, inadequate computing power, and the shear weight of large data sets. Griffen *et al* go on to say that if economists are to provide continuous recommendations of profitability based on crop inputs there must be more adherence to data collection over as broad a range as possible with more incremental levels. Otherwise the models they develop are severely limited by the lack of data imposed by the experimental design. Dynamic simulation modelling will fill in those gaps but in no way be entirely valid until the field checking is done under controlled conditions. In general the production function takes the form of equation 1.

(1) $Yield = f(D_1..D_i \mid X_1..X_i, Q_1..Q_i)$

where D_i = decision input variables (e.g. applied N ha^{-1}, irrigation)
X_i = predetermined input variables (e.g. % A.S.M., soil N)
Q_i = stochastic variables (e.g. precipitation, solar radiation)

(Dillon, 1977)

In risk analysis the use of biophysical models allows us to simulate more data over a longer time series given the availability of weather data and accurate soil parameters. Probability distributions of the uncertain variables such as rainfall, temperatures or solar radiation can then be assigned rather than relying entirely on subjective judgments from producers. Building on the larger data sets, simulated yields can provide simulated gross margins and probability distributions of different production strategies. This was attempted in this report and reported on in a subsequent section. Risk analysis of simulated data does provide important information about the relative risk of different management practices. The stochastic dominance model provided with this document does so to the extent that variance is measured and evaluated through standard deviations of the cumulative distribution functions. This could have useful extension or educational applications with the look-see-what-if scenarios that can be readily recalled from computer memory. Another useful aspect of this type of modelling is that detrending because of changing technologies over time is unnecessary. (Musser and Tews, 1984)

But not all statistical influences are necessarily accounted for in this Bioeconomic approach to modelling. This represents a weakness in the statistical reliability of the simulation of yields. For example CERES-Wheat does not model disease or pest infestations and the variance in simulation will probably understate the yield variance in the real world. This underestimation of variance is also true in experimental versus farm yields due to aggregation. (i.e.

a field crop suffers various levels of damage throughout, which is more accounted for in the experimental block.)

Boggess and Amerling (1983) applied this bioeconomic simulation thinking to an analysis of irrigation investments in Florida. They took biophysical crop growth models to generate yields with weather data. The yields were then incorporated into NPV analysis, and Monte Carlo techniques were used to generate probability distributions of Net Present Values. Historically bioeconomic modelling has been used in a wide range of disciplines. Scheduling inputs such as irrigation water and nitrogen are mentioned several times in the literature. Traditionally they have used the quadratic and the square root forms of the production function in these applications because of their ease of first order differentiation and general tractability. (Koster and Whittlesey, 1971). More recently the Mitscherlich (CERES-Wheat uses one as a major carbon partitioning function) and the Von Liebig functional forms (which are more difficult to manage) have been felt to fit Nitrogen by Water interactions with yield. (Frank *et al*, 1990; Hexem *et al,* 1976; Grimm *et al*, 1987; Ackello-Oguto *et al*, 1985)

Use of 'linear in parameter' functional forms would cut time and resource expenses by use of estimation with least squares regression techniques. (Fuss *et al,* 1978) This may be becoming less of a concern with increased computing power in today's computers, however the interactions among variables of main effect could become unwieldy. Talpaz and Mjelde (1988) suggest the use of "non linear parameter estimation using linear optimization techniques (SAS/ETS) (MINOS 5.0)" and "using quadratic programming to converge on a concave objective function for a global maximum". Model estimation and calibrations could be performed more readily thus making reliability and applicability part of

our present day models. They also suggest models "should account for stochastic weather conditions and provide flexible decision rules to determine ex ante the irrigation strategies to be used." (Talpaz and Mjelde, 1988)

Griffen (*et al*, 1987) outline three key considerations when deciding on an appropriate functional form for bioeconomic models. "Look into functional forms that can have a zero input level for any independent variable and not be forced into subsequent zero output" (i.e. have a positive "Y" intercept). The theory behind this is that something will probably grow if the seed is put in the ground. Otherwise there would be a range of application problem to be constantly aware of when applying the model. The same consideration would apply to the upper end of the independent variable scale. Higher values of D_i (outside the range for which the model was specified) may not be realistic for quadratic and cubic functions. "Allow marginal products to move from positive to negative to fit the agronomic theory that at some point output will decrease as inputs to the growing plant over saturate the growth environment and eventually decrease output" through toxicity or drowning. (Griffen *et al*, 1987) The resistance, hyperbolic and Mitscherlich formulae with their asymptotic convergence of output towards a maximum do not do this, however, there is growing interest in these functions that reveal a "plateauing effect". Some yield interactions may be just as well defined by these nonlinear estimations with no subsequent loss in economic maximization or minimization validity except possibly in the case of dry land nitrogen response. (Frank *et al*, 1990) Their last point is supported by Frank in that the functions must not impose any restrictions on concavity. (Griffen *et al*, 1987) This would be in order to allow unique, economically optimum solutions to production problems over the entire functional "surface". Maximizing profits with first order equations is possible with strict and quasi

concavity. Factor substitution is not lost either with these functional forms and therefore still display similar flexibility as do the polynomial functions that have traditionally been the backbone of bioeconomic crop modelling.

An alternative to the quest for the ultimate single production function was suggested by Boggess (1984); revive the Georgescu-Roegen theory of production (*Amer. J. Agric. Econ.* (54); 279-94) which starts at the concept of elementary processes and builds to the production function. A link to the biological and physical sciences is appealing in this concept. Here output is equal to the following function number 2.

(2) Output = f (R + M + I + W + L + H + K)

where R = Natural Resources M = Materials
I = Maintenance W = Wastes
L = Land H = Labor
K = Machinery

Flows of all functions would blend into one overall function and be used to address dynamic, stochastic production problems. Advantages of this model would include:

1. Stronger foundation for evaluating the results and formulating recommendations.
2. Stochastic aspects of R are explicitly modelled and an opportunity to evaluate various sources of production risk.
3. Timing of inputs is explicit allowing analysis of dynamic input decisions (i.e. Irrigation, Pest Management.)

Disadvantages of the modelling system would be the difficulty in mathematically analyzing something that big and all encompassing. Search algorithms would have to be established to find the optimal input levels.

Agricultural economists' concerns with using these models would be:

- how to appropriately use these models in research,
- how to communicate advantages of these models to other scientists,
- and how to facilitate the gathering of various types of scientists to build the models.

To a certain extent this is happening within the scientific community, even though there are complaints to the contrary, and might in the long run be the route to go to obtain the ultimate user friendly simulation models built by a team of research scientists across several disciplines of Soils, Plants, Economics and the Environment. To a large extent the goal of seeking the ultimate production function is stymied by the lack of resources and interdisciplinary cooperation.

C. WHEAT RESPONSES TO WATER, SOIL MOISTURE AND NITROGEN

In many irrigation studies, evapotranspiration calculations have been used to estimate yield. (Vaux and Pruitt, 1983; Mapp and Eidman, 1975) Others include the following studies. A ratio of actual evaporation to potential evaporation (AE/PE) in conjunction with min-max temperatures was found to give fairly good (r^2=0.77) correlations with wheat yields in western Canada. (Baier, 1973) Minimum temperatures, global radiation and AE/PE were found to give a slightly better (r^2=0.78) fit but the global radiation data was not always available. Global radiation can be estimated from the total bright sunshine hours through a non dimensional Angstrom equation. (see Appendix, File #1)

Talpaz and Taylor (1977) used Kissel's response function, incorporating a stress day concept, with a study on optimal rates of N where there was a probable element of risk about weather and yield responses. A long time series of weather data yielded probability distributions for available soil moisture through the stress day formulae.

(3) $Y = 2674.46 + 27.88 * N - 0.323 * WN - 0.0804 * W^2$

where N = nitrogen in lbs /ac
W = # of stress days in the growing season

$W = \Sigma (1 - (En / Eo))$ for # days from emergence to maturity

En = actual daily evapotranspiration
Eo = potential daily evapotranspiration

Korentager and Berliner (1988) measured moisture stress effects on nitrogen response in wheat for South Africa. Their second order equation also had a measure of evapotranspiration built in.

(4) $Y= \alpha_0 + \alpha_1 S + \alpha_2 N + \alpha_{12} SN + \beta SN^2$ $R^2 = 0.83$ S.E.= 0.341

where N = applied nitrogen (kg ha^{-1})
S = normalized (0-1) value for moisture stress based on equation 4a.

(4a) $\Sigma_i (ET / ET_p)_i^{1/4}$

where i = growth stages 1 - 4
1 = emergence to boot
2 = boot to heading
3 = heading to soft dough
4 = soft dough to maturity

ET = evapotranspiration correlated with rainfall and soil moisture
ET_p = potential evapotranspiration via Penman equation

The evapotranspiration ratio is a main factor determining year to year variability in wheat yields and is a significant factor in explaining how wheat responds to nitrogen. They did not include an N^2 term by itself in the production function because implied N response under high stress levels tended to be linear rather than quadratic. Calibration and validation studies were done a year later to show that the model accounted for 83% of the variation of predicted from

observed yields with 69% of that being due to moisture stress and 25 % due to nitrogen fertilizer levels.

Bole and Freeze (1986) in the use of the RECROP model for barley yields relied on Bole and Pittman's regression equation of 1980.

(5) $Y_B = -2196 + 40.39\ Ws - 0.1027\ Ws^2 + 10.82\ GSP + 0.4908\ N - 0.0412\ N^2 + 0.0242\ WsN + 0.0885\ GSP*N$

where Y_B = yield of barley in kg ha^{-1}
Ws = available spring moisture (May 15th)
GSP = growing season precipitation (May 15th - July 31st)
N = applied nitrogen in kg ha^{-1}

Campbell (*et al,* 1988) also used a fertilizer by available spring soil moisture (AvSpSM) by growing season precipitation (GSP) model.

(6) $Y = -544 + 10.07\ MU \qquad (r^2 = 0.63)$

where MU = GSP + (AvSpSM - HaSM)
and where GSP = growing season precipitation (May 1-July 31)
AvSpSM = $H_2O_{(vol)}$ in spring - lowest $H_2O_{(vol)}$ in study
HaSM = $H_2O_{(vol)}$ at harvest in top 120 cm subtract lowest $H_2O_{(vol)}$ in study

Growing season precipitation as measured in this study and also by Robertson (1974), Zentner and Read (1977), and Bole and Pittman (1980) was the best indicator of spring wheat yields, even more than temperature and AvSpSM. Heapy (1976) found a relationship based on soil moisture stress and applied nitrogen to predict yields of barley. It was the basic quadratic function that he used in his studies as well.

(7) $Y = 16.6 + 0.15863\ N_a + 0.15277\ P_a - 0.00077\ N_a^2 - 0.00196\ P_a^2$

Benbi (1990) suggested in his study of irrigated wheat on sandy soils in India that the decreasing marginal productivity in the quadratic function (8) may be due to "a threshold water supply beyond which water supply increases were

not reflected in increased fertilizer N use, because of limiting factors to production; such as unbalanced levels of or leaching of nutrients".

(8) $Y = 3.71 + 0.515\ N + 13.9\ WS - 0.00368\ N^2 - 0.120\ WS^2$

where N = fertilizer nitrogen (kg ha^{-1})
WS = water supply (cm)

Weisensel *et al*, (1991) in their analysis of risk and crop rotations assumed the quadratic (9) and developed state transformations of next years soil moisture based on the present soil moisture via logarithmic equations (10) and (11).

(9) $Y = \alpha_0 + \alpha_1\ SM - \alpha_2\ SM^2$

where SM = Available Spring Soil Moisture

(10) $\ln SM_{t+1} = 2.021 + 0.2286 \ln SM_t$ (fallow)
(11) $\ln SM_{t+1} = 1.602 + 0.2271 \ln SM_t$ (stubble)

They then used Monte Carlo simulation, comparing expected net returns and relative riskiness of cropping strategies and found that flexcropping based on available spring soil moisture at seeding was most profitable over the long run. The value of Available Spring Soil Moisture knowledge depends on how much confidence the producer has in the measurements of same. These flexcrop strategies based on a break even formula were effective extension tools. Theirs' was:

(12) $Y_s = (Y_f/2) + ((C_s-(C_{sf}+C_f)/2)/P_w)$

where Y_s = yield on stubble
Y_f = yield on fallow
C_s = direct cost of stubble cropping
C_{sf} = direct cost of summerfallowing
C_f = direct cost of fallow cropping
P_w = price of wheat

Which says that if the price of wheat rose, the amount of yield on stubble that would be economically equal to or better than a yield on fallow could be lower,

than if the price of wheat dropped. They also investigated the technique of Markov Chain Dynamic Programming for a Flexcrop decision rule.

Harris and Mapp (1986) suggested a linear equation (13) of rainfall in the spring to be a close approximation to available soil moisture at that time and a yield prediction tool.

(13) $Y = \alpha + 0.22\ R + 2.33\ r$

where α = wilting point of the soil
R = April's rainfall (inches)
r = April's rainfall during the last week (inches)

As reported by Henry (*et al,* 1986) coefficients of determination (R^2) were further increased by the inclusion of growing degree days and water supply in Nitrogen by Yield studies in Saskatchewan. Linear relationships examined extensively in the literature concerning Saskatchewan experiments conclude that "with low available soil nitrogen levels and no moisture stress, the effect of up to 100 kg N ha^{-1} will be almost entirely to increase yields by 25 kg of hard red spring wheat for every 1 kg ha^{-1} of fertilizer nitrogen applied". Halvorson (*et al*, 1987) confirmed this relationship in their compilation of Great Plains and Pacific North West wheat production. Beyond this level of applied nitrogen, plateauing or quadratic relationships to yield were evident in Henry's work although not specifically modeled for dryland wheats. Irrigated soft white spring wheats generally showed the reduction in yield at higher fertilizer nitrogen rates. "Under medium moisture conditions yield could increase slightly while under extremely dry conditions where yields are under 600 kg ha^{-1} nitrogen fertilizer had little effect on yield." (Henry *et al*, 1986) As for moisture effects in the same summary, hard red spring wheats produced approximately 10 kg of grain per hectare for every 1 mm of water consumed with a minimum use of 50 mm before

any grain yield was recognized. The linear relationship of nitrogen held true in this study (see Fig. 4) while consumptive use was not analyzed, although CERES does simulate such values. Standard quadratic functional forms with nitrogen by total available water interactions were the mainstay of Henry's studies as well.

III.) THE BIOPHYSICAL MODEL

A.) AN EXPLANATION of CERES-Wheat

Dynamic growth models of crop plants divide the growing season up into distinct phases of development in order to duplicate the normal differential growth response to the changes in the seasons. Different amounts of carbohydrates are manufactured in and partitioned to various parts of the plant depending on the environmental conditions during the phase. The CERES-Wheat simulation model uses the following phenological events for its phases C1 to C9 (Rickman and Klepper , 1990). The last two phases C6 and C7 are not modelled explicitly in the CERES program.

Table 1. Phases of development with corresponding phenological events used in the CERES family of crop growth simulators

CERES Phase	Phenological Events	BBCH Scale
C8	Sowing to germination	00-05
C9	germination to emergence	05-09
C1	emergence to terminal spikelet initiation	10-15
C2	terminal spikelet to flag leaf	15-40
C3	flag leaf to headed	40-59
C4	headed to beginning of grain fill	59-70
C5	beginning of grain fill to maturity	70-86
C6	physiological maturity to ripeness	86-92
C7	ripeness to sowing	92-100

(Note: The BBCH scale on the right is an internationally recognized numerical system to record the growth stages of plants established by the manufacturers Bayer, BASF, Ciba-Giegy, and Hoerscht.)

This system is at the heart of most mechanistic or process oriented cereal growth models. The length of each phase is determined by the number of Growing Degree Days accumulated from one phase to the next according to equation 14.

(14) $\Sigma ((Tmax + Tmin) / 2) - Base\ ^\circ C$

(base may change with developmental phase but is generally 0°C to 2°C)

Growth or the capture and partitioning of carbohydrates is governed by light interception, nutrients and water uptake, temperature and time of appearance of the plant tissue in question and is discussed subsequently. The accumulation of growing degree days also determines the rate of leaf emergence (phyllochron interval), of tillering (spikes plant^{-1}), and indirectly root development (via the phyllochron interval) for the uptake of water and nitrogen. Water, temperature and nitrogen availability can delay or even reduce tillering and root development. Growth of the grain kernels which constitute yield in this study is made up of the component parts outlined below in equation 15.

(15) plants m^{-2} * spikes plant^{-1} * kernels spike^{-1} * grams kernel^{-1} = grams m^{-2}

These four yield components are all formed during the above growth stages according to figure 1.

CERES-Wheat is a user friendly, menu driven model written and compiled in Microsoft FORTRAN V 4.01 and Quick Basic v 4.0. It is intended to be an "operational model to provide users with:

a) assistance with farm decision making,
b) risk analysis capability,
c) in-year management ability,
d) large area yield forecasting,
e) policy analysis, and
f) definition of research needs." (Ritchie, 1984, p293)

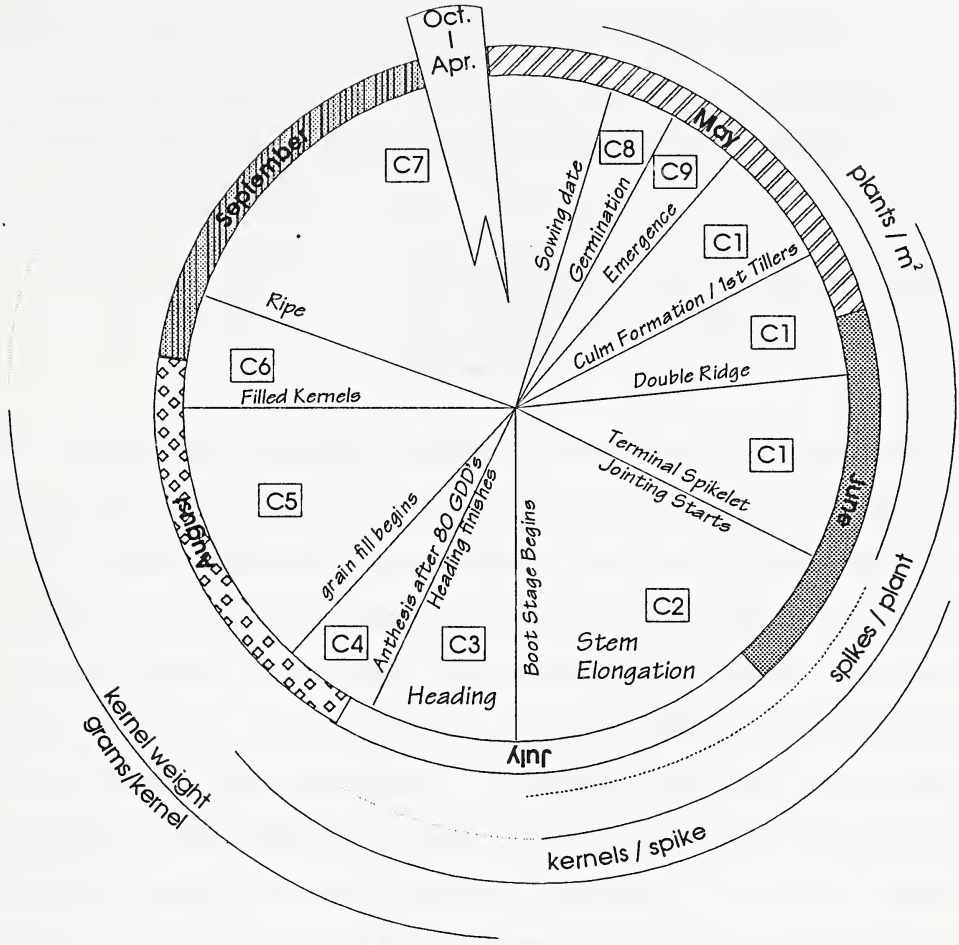


FIG. 1 Phases of development, phenological events and the intervals of wheat yield components in the CERES-Wheat crop growth simulation model. Calendar dates are for illustrative purposes only. The length of any phase is governed by the factors of temperature, solar radiation and daylength.

It is a daily-incrementing, process oriented model of wheat crop growth and development. It is a blend of empirical and mechanistic functional forms, coefficients and scalars. This mixture is necessary at this period of mechanistic crop model building because detailed theoretical knowledge of many inner plant processes is lacking. Simpler first and second order linear equations used to daily produce and partition photosynthates are initialized by water transpiration,

minimum - maximum temperatures, and global sunlight interception. In the CERES-Wheat model photosynthetic rate and carbon manufacture for assimilation into dry matter yield is governed by the state equation 16.

(16) $pcarb = \alpha * \beta\ PAR * (1.0 - \exp(k * LAI))$

where

pcarb	=	photosynthetic carbon (g m^{-2})
α	=	empirically derived coefficient (g MJ^{-1} of PAR)
PAR	=	50 % of Solar radiation (MJ m^{-2})
k	=	extinction coefficient (- 0.85)
LAI	=	leaf area index.

The α coefficient also embodies the effect of transpiration on photosynthesis and is fixed in this model. The $(1 - \exp(k * LAI))$ term in the equation estimates the fraction of photosynthetically active irradiance (PAR) that is intercepted by the wheat crop. Photosynthetic carbon production is further modified by the daily calculated nitrogen and soil water stress indices, and a min/max temperature function to reduce carbon synthesis if nitrogen, water or temperature are deficient at each daily time interval. The gross amount of photosynthates produced are then partitioned between stems, leaves, roots, and grain via empirically derived mechanistic equations depending on the stage of growth calculated by the model. Root growth is calculated in terms of total length per soil layer and total depth of penetration. Soil profile information provided by the user governs the preference for root penetration in each soil layer. Water balance in the model is a daily budgeting procedure of additions less deletions to equal storage. Additions of rain, snow, or irrigation are depleted by runoff, root extraction, drainage or infiltration to lower soil layers, and evaporation. Here too a combination of first, second and third order equations daily calculate the variables. Calculation of vernalization, winter hardiness and winter kill are also part of the model if winter cultivars are specified in the genetics file (see Appendix, File #2)

Leaf area index (LAI) is also estimated daily from leaf area expansion, leaf senescence, and tiller death. Carbohydrate partitioning continues to be directed towards the grain once the reproductive stage of growth is reached (phase C4 in Figure 1). The plant weight at flowering determines the number of kernels per plant. The time and temperature accumulated for dry matter distribution governs the kernel weight. Both kernels per plant and grams per kernel are multiplied with the number of plants per square metre to give a final grain yield (equation 14). Nitrogen balance associated with the growth of wheat allows for contributions and losses of organic and mineral nitrogen. Incorporated straw, mineralized root material and inorganic nitrogen, along with 10 different types of mineral fertilizer nitrogen and their subsequent nitrification account for the additions to soil N. Bowen (*et al*, 1993) explored the validity of a subroutine in the CERES-Maize model that decomposed plant residue and added organic nitrogen to three pools of carbohydrates, celluloses, and lignins. Each pool had its own first order decay constants which governed the daily release of nitrogen into the system. Their conclusions found the simple assumptions in the empirical equations to be fairly reasonable in their prediction of available nitrogen mineralization for cereals but needed modification if legume green manure was the principle organic matter addition in the system. Similarly nitrification is modeled in CERES-Wheat by a first order rate decomposition equation to deplete the ammonium pool and build up the plant available nitrate pool in each soil layer. Losses include subroutines for denitrification, immobilization, urea hydrolysis, and uptake by plants. Stress indices (zero to one) of both water and nitrogen factors affecting photosynthesis, and leaf expansion and growth at all growth stages are calculated and displayed at the end of model runs. The CERES-Wheat model is capable of either simulating nitrogen balances and effects of nitrogen on crop growth or switching to allow

adequate nitrogen levels throughout the simulation and thereby pose no nitrogen stress to the plants.

B.) INPUT into the CERES-Wheat Model

The capacity to simulate multiple-year or multiple-treatment scenarios without requiring additional keyboard inputs made this project possible. The program called for seven ASCII text files of climatic, genetic, agronomic, and management data to complete the necessary simulation runs. They are described in the Appendix under the two headings of States of Nature and Decision Variables.

C.) OUTPUT generated by the CERES-Wheat Model

The output from CERES-Wheat gives a detailed daily look at the growth of the wheat plant and its component parts. The nitrogen balance in the grain, the vegetative parts of the plant and the top five layers of soil are generated over the simulated time and summed at the end of the simulation run. An indication of the growth stage at which the plant was stressed for nitrogen and water is tabulated in the summary output file. Soil water content and weather related characteristics are tracked over time. Colour graphics facilities for interactive display of summary and detailed crop, soil water, and nitrogen outputs have been added to this recent version to make modelling a visual learning experience (Godwin *et al*, 1990). Below the major variables recorded by the output of the model are listed.

Crop Growth Output (per day or per simulation interval unless otherwise indicated)

- days to maturity ---------- (days)
- total grain yield ---------- ($kg\ ha^{-1}$)
- final grains ---------- (m^{-2})
- final grains ---------- ($spike^{-1}$)
- total biomass yield ---------- ($kg\ ha^{-1}$)
- total straw ---------- ($kg\ ha^{-1}$)
- leaf area index ---------- ($m^2\ m^{-2}$)
- tillers ---------- (m^{-2})
- root, stem, leaf ---------- ($g\ plant^{-1}$)

Nitrogen Balance Output

- soil nitrogen uptake by the plant ---------- ($kg\ N\ ha^{-1}$)
- nitrogen uptake for straw and grain separately ---------- ($kg\ N\ ha^{-1}$)
- grain nitrogen ---------- (%)
- soil nitrate and ammonium levels in the top layers ---------- ($\mu g\ N\ g^{-1}$)
- nitrogen and water stress levels at five growth stages

Weather and Water Balance Output

- evaporation ---------- (mm)
- transpiration ---------- (mm)
- global solar radiation ---------- (MJ)
- minimum and maximum temperatures ---------- (°C)
- rainfall from emergence to maturity each year ---------- (mm)
- total rain from start of simulation to maturity each year ------ (mm)

CERES-Wheat has a few drawbacks in its usefulness as a simulation model of wheat growth. The fact that it does not modify maturity dates due to rain and applied nitrogen is not realistic. Days to maturity would normally lengthen with increased precipitation, delayed time of seeding, lower heat units input and timing of these inputs. The model does not take into account the soils being frozen over the winter so winter tests may be invalid in the northern prairies. Runs of the simulation model were done over the winter months (September to April) to estimate the available spring soil moisture (AvSpSM) on April 15th each year in this paper. Real field data would be needed to accurately validate the model output for these multi-year simulations.

CERES-Wheat has no way of accounting for costs associated with pest damage and control, fixed costs of production or other variable costs that would have changed with varying weather conditions or soil moistures. As well this model cannot be used for herbicide research where the efficacy of the new herbicide is unknown. These factors must be left for the true integrated models of the future.

D.) DESCRIPTION OF THE SIMULATION EXPERIMENT

INITIALIZATION

Initialization of the variables in the model was accomplished by setting reasonable values for common wheat cropping practices in the Edmonton area, using soil profile data from the University of Alberta research plots at Ellerslie, and converting weather data from the nearby Edmonton International Airport to a format accepted by CERES-Wheat. These variables were recorded in tabular form according to the file number as read by the model program and broadly grouped under the general headings of States of Nature and Decision Variables in the Appendix. Several assumptions were made since detailed field data was not available for this time period.

An amount of straw equal to 3000 kg ha^{-1} was set each year based on an average crop of 3000 kg of grain per hectare and incorporated to a depth of 15 cm. The multi-year runs of the model did not automatically update this figure based on the previous year's grain yield. A grain to straw ratio of 1:1 was suggested in the program documentation but this would have had to be input manually at the end of each year run, increasing computational time tremendously. A C:N ratio of 80:1 was used to indicate a medium high rate for cereal straw. (Stoskopf, 1985)

Root matter addition was input at 300 kg ha^{-1} each year but was later learned to be in error as this would be a typical summerfallow residue figure according to the CERES documentation. For stubble cropping cereal crops the model suggested 20 % of the previous years' grain yield which again would have had to be input manually at the end of each year run.

The simulations were started on April 15th of each year, and the date of planting was May 10th, at a rate of 300 plants m^{-2}, to a depth of 5 cm. This could have been lighter and deeper on dry years and to be modelled agronomically for a multi-year run should probably change according to the known weather data. However, for consistency these cultural practices were kept constant throughout.

On May 1st of each simulation year anhydrous ammonia (82-0-0), which is in reality knifed into the soil at or below seed bed depth, was instead "incorporated" into the top 15 cm. CERES-Wheat made the simplifying assumption that the fertilizer was uniformly incorporated into the layer of placement. This version of the model did not take into account the positive band placement effects to plant growth. It was further assumed that the soil profile was low in nitrogen in the spring before planting each cropping year. CERES-Wheat did not model the winter balance of nitrogen in the multi-year runs but instead required the parameters to be set each year as to how much soil nitrogen was present at the beginning of the simulated year. It was assumed the amount of soil mineral nitrogen in the whole profile (120 cm) was a low value of 51 kg N ha^{-1} with proportionally more in the top three soil layers and exponentially less in the bottom layers. (see Appendix, File #6).

A phyllochron interval (indicating the timing of leaf emergence) was set at the recommended value of 95 DTT (degrees thermal time) per leaf for the lack of any other experimental data for the Katepwa variety of wheat.

CALIBRATION

The variety Katepwa wheat was calibrated using the 1990 Cereal and Oilseed Advisory Committee Regional Variety test plot data from the Ellerslie site. Dates to anthesis and maturity, and thousand kernel weight were obtained from this source (Cereal & Oilseed, 1990). Genetic coefficients (see Appendix, File #2) scaled the physiological growth characteristics of vernalization (P1V), photoperiodism (P1D), grain filling duration to estimate the time of maturity (P5), kernel number (G1), kernel filling rate (G2), and spike weight (G3). The scale values were linearly converted into biological values with appropriate units within the model. Details for the calibration process were found in the CERES-Wheat handbook (Godwin *et al*, 1990) and the scaling algorithms were located in the ECHO routine of the FORTRAN source code. These coefficients were modified and were calibrated to known field data. Counts of typical tillering rates of Katepwa wheat were used from the Olds College demonstration plots (unpublished data) since it was not recorded at the Ellerslie site.

VALIDATION

Yields for as many of those years at Ellerslie that Katepwa, and its parent crop Neepawa, were grown were compared with the modelled output yield ranges for all combinations of applied nitrogen and available spring soil moisture. Comparison of these yields was limited at best as initialization values for individual years needed to do a proper detailed validation were not sought

out. Such yearly initialization data would need to be found to dispense with the assumptions above and make the yearly runs more accurate. In this way predicted yields could be fairly compared with the actual field yields.

E.) PRODUCTION FUNCTION DETERMINATION

The intermediate problem to be solved here was the specification and estimation of a functional form for the growth of wheat with input factors of applied nitrogen and total available water including precipitation. As mentioned above by Griffen (*et al*, 1987) it may well be impossible to determine the true functional form at this point in bioeconomic modelling as all the input factors and interactions are not yet known or fully understood. The levels of applied nitrogen fertilizer were part of the decision variable set of the CERES-Wheat input files. The model was instructed to increment values of 20, 40, 60,.... 180, & 240 kilograms per hectare for each of the 30 years of weather data (see Appendix, File #7). This variable set was chosen because it covered the range of commonly applied rates in the field and extremely high rates (+100 kg ha^{-1}) to push the model.

The other side of this matrix was total available moisture which included the available spring soil moisture (AvSpSM) and any growing season precipitation. The AvSpSM values were set into the CERES model in increments of 10 % available soil moisture by volume (i.e. 10 % of the moisture available between wilting point and field capacity). Therefore a value of 100% AvSpSM would represent an entire soil profile at field capacity. A 10 % value would indicate each layer of the entire soil profile just above the wilting point. Zero percent did not mean absolutely no water, just no "available" water for the roots to extract. These two extremes are unlikely to be found for very long if at

all in real conditions but to test the model fully these 10 units of 10% AvSpSM were chosen. Based on bulk density values for each layer, upper and lower limits of moisture holding capability ($m^3\ m^{-3}$) were set by the model. The amount of extractable soil water ($m^3 m^{-3}$) was then divided into ten equal parts within each layer. These deci-values were the basis of the initial soil water values (file #6 in Appendix) for the 30 year simulation.

Yields were then simulated over the full range of available spring soil moisture and incremental nitrogen fertilizer application rates for 27 years of the experiment. (1968, 1982, and 1983 generated days to maturity of 170, 0, and 230 respectively when included in the initial 30 year weather file and were therefore eliminated to allow the multi-year simulation to run without these errors.) Yield values for each combination of applied nitrogen rate, and available spring soil moisture percentage, along with year, cumulative evapotranspiration, total rainfall, days to maturity, and rainfall from emergence to maturity values were taken from the output files and combined with further data manually gathered from the weather files (i.e. average temperature for the growing season, total global solar radiant energy, and precipitation in various combinations over various periods during the year). Based on the functional form needed to fit the yield table for the stochastic dominance test, the coefficients of multiple determination (R^2), and the coefficients of correlation (r) it seemed that equations in the form of (16) (17) or (18) would fit fairly close to the data. The coefficients for these equations are summarized in Table 2

(16) $Y = \alpha_0 + \alpha_1\ NRATE + \alpha_2\ TAM + \beta_1\ NRATE^2 + \beta_2\ TAM^2$

(17) $Y = \alpha_0 + \alpha_1\ NRATE + \alpha_2\ TAM + \beta_1\ NRATE^2 + \beta_2\ TAM^2 + \beta_3\ NRATE^2 * TAM^2$

(18) $Y = \alpha_0 + \alpha_1\ NRATE + \alpha_2\ TAM + \beta_1\ NRATE^{1/2} + \beta_2\ TAM^{1/2} + \beta_3\ NRATE^{1/2} * TAM^{1/2}$

An explanation of the variables follows. Variables in Table 3 were created by the CERES-Wheat program, those in Table 4 were extracted manually from the weather files for each year and combined with Table 3 values using Lotus 1-2-3 and Personal Editor (PE2), and Table 5 variables were generated by the statistical software, CoStat, from the other variables. Ordinary least squares regression analyses were carried out with the independent variables to yield and summarized in Table 6. See Table 7 for the results of the correlation matrix of variables.

Table 2 Equation coefficients for two quadratic and one square root function from CERES-Wheat yield data.

Equation	(16)	(17)	(18)
α_0	-12.71	- 12.107	- 24.327
α_1	0.02378	0.02378	-0.01933
α_2	0.03891	0.03891	-0.03785
β_1	- 6.477E-05	- 1.001E-04	-0.4431
β_2	- 2.417E-05	- 2.6165E-05	1.9051
β_3		1.1623E-10	0.0425
R^2	0.6853	0.7006	0.714

Adding more variables that were connected to rainfall (i.e.,TRAIN, PRECIP) only led to erratic shifts in the estimated coefficients for the variables in equation 16 or a reversal in sign of the coefficients. This suggested a problem with multicolinearity, explained by the relationship, T.A.M. = A.S.M. + TRAIN. TRAIN was highly correlated with all the other rainfall variables (r = 0.8 - 0.9). Therefore these basic quadratic and square root functions were left simple and

uncomplicated largely for the purposes they were intended for, that being their inclusion in the stochastic dominance model. Adding variables into this model based on stochastic temperatures or cumulative evapotranspiration was outside the boundaries of the task at hand even though they may have led to a better fit.

TABLE 3 Variable names and descriptions for data generated by the CERES-Wheat simulation

YIELD	= wheat grain yield in (t ha $^{-1}$).
NRATE	= elemental Nitrogen (kg ha $^{-1}$) applied on May 1st.
ASM	= Available Spring Soil Moisture (%vol) as of April 15th of each year.
CET	= cumulative evapotranspiration in millimetres.
TRAIN	= total rainfall from the start of the simulation on April 15th to maturity of the crop.
DM	= number of days to maturity for a given year.
MRAIN	= Total millimetres of rain (mm) for the period from emergence to maturity

TABLE 4 Variable names and descriptions for data gathered from the Edmonton International Airport weather files

MJ	= Total megajoules of global solar radiation for the period May 10th to August 31st.
AVGT	= Average daily temperature (°C) for the period May 10th to August 31st.
STDT	= Standard deviation of the average temperature (°C) for the period May 10th to August 31st.
PRECIP	= Total millimetres of rain (mm) for the period May 10th to maturity.
WRAIN	= Winter precipitation (mm) from September 1st to May 31st of the following year.
YRAIN	= yearly precipitation (mm) from January 1st to December 31st.
CYRAIN	= Crop year precipitation from September 1st of the preceding fall to maturity.

TABLE 5 Variable names and descriptions for data generated by the statistical software

NRATE2	= square of the NRATE value.
NRATE½	= square root of the NRATE value
ASM2	= square of the ASM value.
TAM	= ASM converted to millimetres and added to TRAIN.
TAM2	= square of the Total Available Moisture (T.A.M.).
TAM½	= square root of the Total Available Moisture (T.A.M.)
PRECIP2	= square of the PRECIP value.

TABLE 6 Statistical summary for 36 regression analyses performed on the CERES-Wheat data set.

		R^2(adj)	S.E.E.
1.	NRATE	0.1204	1.3097
2.	NRATE,ASM	0.3990	1.0826
3.	NRATE,NRATE2	0.1628	1.2778
4.	NRATE,NRATE2,ASM	0.4415	1.0437
5.	NRATE,ASM,NRATExASM	0.4162	1.0670
6.	NRATE,NRATE2,ASM,ASM2,NRATExASM	0.4645	1.0219
7.	# 6 + DM	0.5832	0.9015
8.	# 6 + DM,AVGT	0.5868	0.8977
9.	# 6 + DM,AVGT,MJ	0.5944	0.8894
10.	# 6 + DM,AVGT,MJ,MRAIN	0.7502	0.6980
11.	# 6 + DM,AVGT,MJ,TRAIN	0.7910	0.6384
12.	# 6 + DM,AVGT,MJ,PRECIP	0.7961	0.6305
13.	# 6 + WRAIN	0.4851	1.0021
14.	# 6 + WRAIN,AVGT	0.5921	0.8919
15.	# 6 + WRAIN,AVGT,MJ	0.6035	0.8793
16.	# 6 + WRAIN,YRAIN	0.6697	0.8025
17.	# 6 + WRAIN,PRECIP,DM	0.7950	0.6323
18.	# 6 + WRAIN,CYRAIN	0.8087	0.6108
19.	# 6 + CYRAIN	0.7628	0.6801
20.	# 6 + CYRAIN,AVGT	0.7837	0.6495
21.	# 6 + CYRAIN,AVGT,MJ	0.7882	0.6426
22.	# 6 + CYRAIN,PRECIP	0.7932	0.6350
23.	# 6 + CYRAIN,PRECIP,DM	0.8023	0.6210
24.	# 6 + CYRAIN,PRECIP,MJ	0.8046	0.6173
25.	# 6 + CYRAIN,PRECIP,AVGT	0.8103	0.6083

The preceding 25 regressions were run using Shazam. The following 11 regressions were done with CoStat which does not give R^2 adjusted or standard error of the estimate values.

		R^2
26	NRATE,NRATE2,TAM,NRATE2xTAM	0.6830
27	NRATE,NRATE2,TAM,TAM2 (equation #16)	0.6854
28.	NRATE,NRATE½,TAM,TAM½	0.6860
29.	# 27 + NRATExTRAIN	0.6899
30.	# 27 + NRATExPRECIP	0.692
31.	# 27 + NRATExTAM	0.709
32.	# 27 + NRATE2xTAM2 (equation #17)	0.7006
33	# 28 + NRATE½xTAM½ (equation #18)	0.714
34.	# 27 + PRECIP	0.759
35.	# 27 + PRECIP,NRATExPRECIP	0.7701
36.	# 27 + PRECIP,NRATExTAM	0.783

TABLE 7 Correlation matrix of variables to yield

VARIABLE NAME	r
CET	0.8265
TAM	0.710
PRECIP	0.5513
CYRAIN	0.5458
TRAIN	0.5444
ASM	0.5279
MRAIN	0.4847
STDT	-0.4812
YRAIN	0.4449
NRATE	0.3475
AVGT	-0.3379
DM	0.3232
MJ	0.2377
YEAR	0.1677
WRAIN	0.1439

IV.) THE ECONOMIC MODEL (STOCHAST)

The crop producer is continually faced with decisions to make, usually with regard to profit maximization or cost minimization. He is also faced with known inputs that can be acted upon (either discrete or continuous), along with unknown inputs. These unknown ones, over which he has little or no control, are the outcome states of nature that are often random (stochastic) in occurrence. The water input into the CERES-Wheat model for example is all rain fed and therefore fits into this latter category. To the extent that a probability can be put to these states of nature a known amount of risk is involved in making decisions in this environment. So even though the vagaries of nature can lead to random returns on the farm one can still deal with them in a probabilistic sense. We don't often have time, interest or energy to search out the infinite number of actions or states of nature, therefore we limit our focus on a few of the more obvious or potentially attractive. In this study only two inputs were investigated, that being the action of applying ten levels of fertilizer nitrogen to a wheat crop in the event of various levels of available soil moisture.

The decision or action that a dryland wheat producer takes, in regards to the amount of applied nitrogen, will produce various yields or consequences depending to a large extent on the available moisture in the spring and the ensuing precipitation patterns for that year. The production function (15) above captured that consequential relationship in Table 8 where the yields are a result of the Actions (A_n) taken in years where the Total Available Moisture (Q_i) was low, medium or high. The following tables and figures are also found in the STOCHAST Lotus 1-2-3 worksheet model found in diskette form in the appendix of this paper. At least 2 Mb of expanded RAM memory and as much conventional memory as possible is needed to load this large spreadsheet.

Table 8 Wheat yields (kg ha^{-1}) due to applied nitrogen levels (A_n) and total available moisture (Q_i).

Outcome States of Nature	Actions $A_{(n)}$ kg N ha^{-1}				
	(A_1) 20	(A_2) 75	(A_3) 130	(A_4) 185	(A_5) 240
Low T.A.M. (Q_1)	0.728	1.476	1.833	1.798	1.370
Med.T.A.M. (Q_2)	1.808	2.787	3.374	3.569	3.372
High T.A.M. (Q_3)	2.406	3.615	4.431	4.857	4.890

Note: $Q_{(i)}$ are set at 450 mm, 550 mm, and 650 mm respectively. $A_{(n)}$ values can be changed interactively in the STOCHAST worksheet model

Table 9 from the STOCHAST worksheet model shows the gross margin payoff matrix and the probability of the states of nature (T.A.M.) occurring in the study site. The gross margins are a result of the calculated yields of wheat multiplied by the price for wheat less the applied rates of nitrogen multiplied by the price per kilogram of nitrogen. Both input prices and probability levels of T.A.M. can be set by the user of the STOCHAST worksheet model.

Table 9. Gross margin payoff matrix due to applied nitrogen levels (A_n) and total available moisture (Q_i).

Outcome States of Nature	$P(Q_i)$	Actions $A_{(n)}$ kg N ha^{-1}				
		(A_1) 20	(A_2) 75	(A_3) 130	(A_4) 185	(A_5) 240
Low T.A.M. (Q_1)	0.20	$65.57	$120.62	$136.48	$113.15	$50.64
Med.T.A.M. (Q_2)	0.43	$173.64	$251.70	$290.58	$290.27	$250.78
High T.A.M. (Q_3)	0.37	$233.37	$334.45	$396.34	$419.05	$402.58

Note: $P(Q_i)$ indicates the probability of the state of nature occurring

Table 10 indicates the Ellerslie site conditional probabilities that a poor (Z_1), good (Z_2), or excellent (Z_3) level of available spring soil moisture occurred given the events of low (Q_1), medium (Q_2), or high (Q_3) T.A.M.. Total available moisture values are based on estimated spring soil moisture and total precipitation for the growing season from the CERES-Wheat model output. The probability of T.A.M. ($P(Q_i)$) was multiplied by each conditional probability ($Z_j \mid Q_i$) to give the results in the joint probability section of Table 11 . These joint probabilities were then used to weight the gross margin payoffs from Table 9 in the calculation of the expected or mean gross margins (E) and their standard deviations (V) for each of the possible 125 strategies in the model. (see Table 12)

Table 10. Conditional probabilities of a particular spring soil moisture level (Zj) given a particular state of nature (Q_i)

Outcome States of Nature	Spring Soil Moisture Level (Zj)		
	Z_1 Poor	Z_2 Good	Z_3 Excellent
Low T.A.M. (Q_1)	0.167	0.333	0.500
Med.T.A.M. (Q_2)	0.308	0.384	0.308
High T.A.M. (Q_3)	0.000	0.364	0.636

Table 11. Joint probabilities of spring soil moisture (Z_j) and total moisture levels (Q_i)

Outcome States of Nature	Spring Soil Moisture Level (Zj)			Probability of Sates of Nature $P(Q_i)$
	Z_1 Poor	Z_2 Good	Z_3 Excellent	
Low T.A.M. (Q_1)	0.07	0.03	0.10	0.20
Med.T.A.M. (Q_2)	0.13	0.17	0.13	0.43
High T.A.M. (Q_3)	0.00	0.13	0.23	0.37
Marginal Probability of Prediction $P(Z_j)$	0.20	0.33	0.47	1.00

Table 12 The first six strategies and unsorted gross margin payoffs showing the joint probabilities that make up the probability density functions. Means and standard deviations are shown for each strategy as calculated in the STOCHAST model.

Strategies ->	(111) 1	(112) 2	(113) 3	(114) 4	(115) 5	(121) 6
GMP's						
$65.57	0.200	0.100	0.100	0.100	0.100	0.133
$173.64	0.433	0.300	0.300	0.300	0.300	0.266
$233.37	0.366	0.133	0.133	0.133	0.133	0.233
$120.62		0.100				0.066
$251.70		0.133				0.166
$334.45		0.233				0.133
$136.48			0.100			
$290.58			0.133			
$396.34			0.233			
$113.15				0.100		
$290.27				0.133		
$419.05				0.233		
$50.64					0.100	
$250.78					0.133	
$402.58					0.233	
MEAN -->	$173.92	$213.42	$234.63	$237.56	$222.20	$204.08
STD -->	$60.36	$84.78	$107.03	$117.43	$117.56	$78.19

Table 13 Sorted gross margin payoffs from table 12 with their corresponding joint probabilities that make up the probability density functions for each strategy.

Strategies ->	(111) 1	(112) 2	(113) 3	(114) 4	(115) 5	121) 6
GMP's						
$50.64					0.100	
$65.57	0.200	0.100	0.100	0.100	0.100	0.133
$113.15				0.100		
$120.62		0.100				0.066
$136.48			0.100			
$173.64	0.433	0.300	0.300	0.300	0.300	0.266
$233.37	0.366	0.133	0.133	0.133	0.133	0.233
$250.78					0.133	
$251.70		0.133				0.166
$290.27				0.133		
$290.58			0.133			
$334.45		0.233				0.133
$396.34			0.233			
$402.58					0.233	
$419.05				0.233		
Strategies ->	(111)	(112)	(113)	(114)	(115)	(121)

Whitmore and Findlay (1978) state that the consequences for a given course of action can be viewed as a lottery or a gamble, each having a specific probability. In this study the lotteries are viewed as strategies to apply certain rates of Nitrogen fertilizer (A_n) given a particular level of spring soil moisture (Z_j). The strategies are identified by a three digit number in parentheses ($Z_1Z_2Z_3$). Stochastic dominance analysis will show which action has the larger expected payoff over the long run. The number of strategies that could conceivably result from applying a chosen set of actions to the many different predicted states of nature is equal to the number of actions raised to the power of the states of nature. It can be seen that the 27 strategies resulting from a simple three action by three states of nature matrix jump dramatically to 3125 strategies if five actions were considered along with five states of nature: (5^5=3125). A ten by ten decision model would have far too many strategies to evaluate. For the purposes of this part of the study five fertilizer nitrogen application rates are considered with three levels of total available moisture at any one time. Any larger matrix than the resulting 125 strategies leads to computational problems with the memory resources available in the disk operating system of the IBM compatible computers.

The means and standard deviations of the 125 strategies are graphically represented in the model with an example shown in Figure 2 to give a picture of how the strategies compare to each other for a Mean Variance (EV) analysis. An EV analysis refers to the comparison of the expected or average returns with variation (in this study, deviation) from that expected value. Some quantifiable comparison of the strategic outcomes is necessary to narrow the field of choices to an efficient set which maximizes the producers utility function. It is best if these choices are definite and not vague, and that the preference for any more than two strategies is transitive.

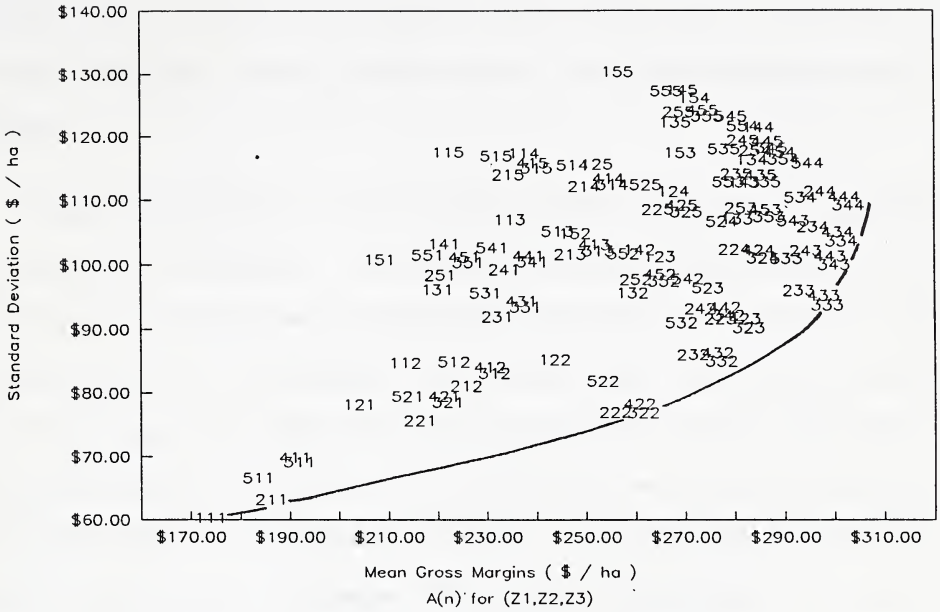


Fig. 2 Scatter graph of 125 strategies using 5 fertilizer levels in 3 events plotted according to EV criteria. The three digit numbers represent the fertilizer actions (A_n) appropriate for the three levels of spring soil moisture (Z_n). Solid line represents the EV frontier.

An evaluation of the strategies using EV criteria is simplified by looking for those strategies that lie along the EV frontier in Figure 2. This frontier depicts those points that represent the highest level of return for a given level of risk (standard deviation) or conversely the lowest level of risk for a given level of return. Risk averse individuals would chose a strategy at the lower left end of the frontier: (i.e. strategy (111) for low risk and corresponding lower returns) while risk neutral persons would chose a strategy with the highest mean gross margin return regardless of the level of risk (i.e. strategies (333) to (344)). Such an analysis assumes that the probability density functions from which the means and the standard deviations are calculated are approximately normal. Since the

joint probabilities in Table 11 came from the random system input variables of available spring moisture and growing season precipitation, it is likely a stochastic dominance criteria is better suited to identifying the efficient set of strategies.

Stochastic as mentioned above means random with respect to a variable; involving chance or probability. Stochastic herein refers to the probability of soil moisture and precipitation events happening in the future as predicted by the frequencies collected in the analysis of the weather data. Since these variables account for a large part of the variance in the production function calculated in the previous section (see equations 1-6 of Table 6) we can assume that the gross payoffs will also be stochastic or randomly distributed if the same function is used to predict yields in the future. "Evaluating those strategies that produce random outcomes is an approach that allows for the ordered pairwise comparison of risky prospects." (Mjelde and Cochran, 1988) The strategy probability density functions are sorted according to the gross margin payoffs (Table 13) and converted to cumulative distribution functions (CDFs) (Figure 3) and cumulative of the cumulative distribution functions (C-CDFs) (Figure 4) for analysis by first and second degree stochastic dominance criteria, respectively. These criteria are ones of pairwise comparison of strategy CDFs or C-CDFs to find those that return as high as or better than all the rest (Bauer, 1988) for all possible levels of "x" or nitrogen application in this study. A strategy represented by a probability density function "f(x)" is said to have first degree stochastic dominance over another strategy represented by "g(x)" when the integral of its corresponding CDF, at any value of x, is less than the corresponding integral of the CDF for "g(x)". Mathematical integration by parts is represented by equation 18 .

$$(18) \quad \int_{-\infty}^{x} [(g(x) - f(x))]\, dx \geq 0$$

(for all x and the inequality must be strict for at least one value of x)

Graphically Figure 3 shows that the difference between the dominated and the dominant strategies is positive for at least one value of x along the cumulative distribution function.

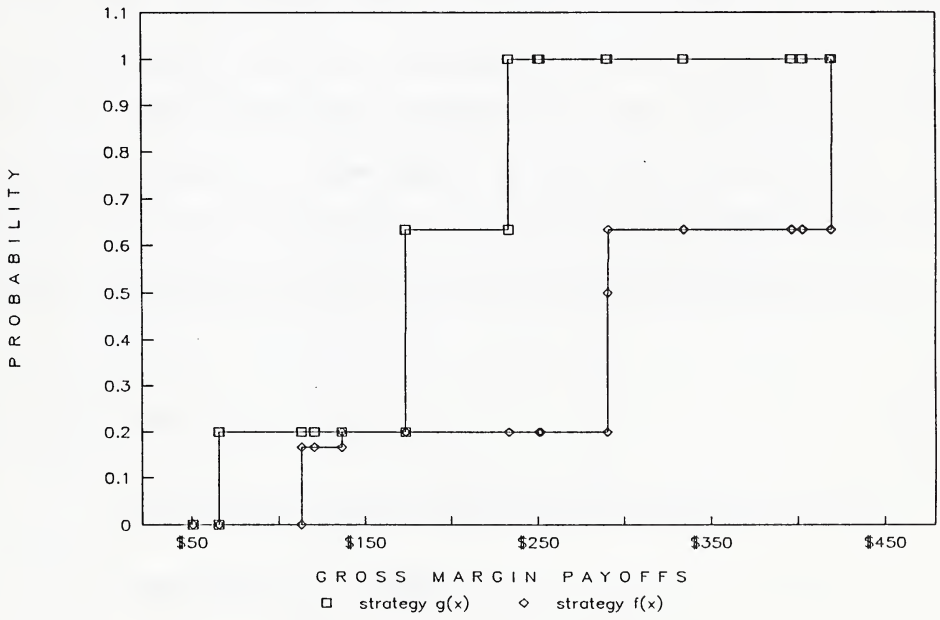


Fig. 3 Cumulative distributions showing first degree stochastic dominance by f(x) over g(x)

This means in part that the mean gross margin payoff for strategy "f " is greater than that of "g " and lies to the right of the dominated strategy. All such CDFs that lie to the right of another CDF and do not cross to the left of another strategy's CDF are said to be first degree stochastically dominate (F.D.S.D.) and

can be included in a set of strategies that is considered to be more efficient for the crop producer to follow in the long run regardless of his risk preference. This type of risk handling looks only at maximizing expected return and is indifferent to the risk (variance) involved in attaining these goals.

The second criteria called second degree stochastic dominance (S.D.S.D.) calculates the efficient set of strategies for risk averse individuals who want to maximize net returns but also take risk (variance) into account when making decisions. A subset of the F.D.S.D. set of strategies may not net a sufficiently high rate of return for the amount of risk involved (e.g. $\mu f \leq \mu g$ but $\sigma f \leq \sigma g$) and thereby "g" will be eliminated by this criteria from the F.D.S.D. efficient set. Mathematically the cumulative of the CDFs used for the F.D.S.D. analysis are compared in a like manner to one another and are said to be dominant when they lie to the right of and never cross less dominant distribution functions. Mathematical integration by parts is represented by equation # 19 .

$$(19) \quad \int_{-\infty}^{x} [(G(x) - F(x))]\, dx \geq 0$$

(for all x and the inequality must be strict for at least one value of x)

$$\text{where } F(x) = \int_{-\infty}^{x} f(x)dx$$

Graphically the functions of F(x) and G(x) are shown in Figure 4 below.

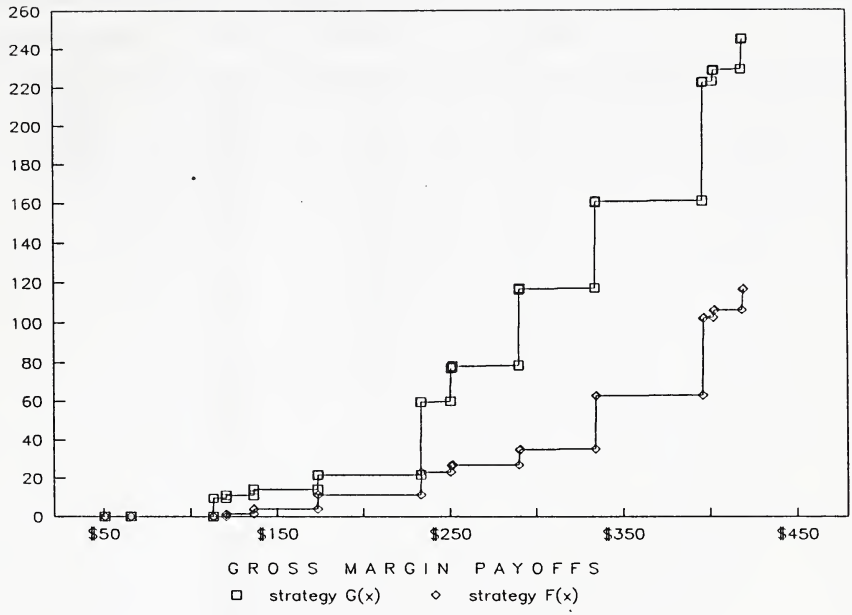


Fig.4 Cumulative of the cumulative distributions showing second degree stochastic dominance by F(x) over G(x)

A third degree stochastic dominance criteria would further reduce the efficient set for any strategies that had similar means and variances and could not be seen to dominate at either the first or second degree levels of stochastic dominance criteria (Whitmore and Findlay, 1978). This criteria was not investigated in this model.

After all the possible pairwise comparisons of the 125 strategies have been completed by the STOCHAST model the F.D.S.D. and S.D.S.D. strategies are sorted and listed as in Table 14. Strategies followed by a zero value represent those that are dominant in either the first or the second degree. If a negative one value follows a strategy in either of the F.D.S.D. or S.D.S.D. columns then that strategy is dominated by at least one other strategy according to the criteria set out above for first or second degree stochastic dominance.

Table 14. F.D.S.D. and S.D.S.D strategies sorted in STOCHAST worksheet model.

2nd°Dominant	STRAT.	F.D.S.D.	S.D.S.D.
YES	333	0	0
YES	334	0	0
YES	343	0	0
YES	344	0	0
	253	0	-1
	324	0	-1
	354	0	-1
	423	0	-1
	453	0	-1
	111	-1	-1
	112	-1	-1
	113	-1	-1
	114	-1	-1
	115	-1	-1
	°		
	°		
	°		
	551	-1	-1
	552	-1	-1
	553	-1	-1
	554	-1	-1
	555	-1	-1

V.) RESULTS AND DISCUSSION

Results of the CERES-Wheat Output

Yield graphs of NRATE and T.A.M. were assembled and presented in Figures 5 - 8. The NRATE by yield graphs (Fig. 5) segregate the 27 years of data into the three total available moisture levels used in the stochastic dominance model. (i.e. low (Q1), medium (Q2), and high (Q3)). A plateau effect is evident at the 4.2 tonne, 4.8 tonne and the 5.8 tonne yield levels respectively. The year 1977 was the highest yielding year even though it had a medium amount of T.A.M., and may have skewed the data to the higher yields for that moisture class. The extreme variability between years is evident by the scattering of data points over a wide range especially in the low T.A.M. years. The plateau effect occurred above the 120 kg N ha^{-1} application rate when total available moisture was low (<500 mm). When the total available moisture was at a medium level the plateau effect started around the 140 kg N ha^{-1} rate. For optimal to wet conditions (> 600 mm T.A.M.) the plateau effect began at the 140 kg ha^{-1} rate of applied nitrogen.

The linear portion of the CERES-Wheat output from 20 to 120 kg N ha^{-1} showed a similar rate of yield gain per nitrogen added (i.e. 25:1) as the literature cited by Campbell (*et al*, 1988) and Halvorson (*et al*, 1987) for Saskatchewan and the north-western U. S. A. A range of 33 to 50 kg N ha^{-1} was needed to yield one tonne of wheat in those studies. The CERES-Wheat average was 40 kg N ha^{-1} per tonne of wheat. (Fig 5)

With respect to the total available moisture (Fig. 6) a linear spread of the multi-year data was evident across the total available moisture regimes. Any plateauing effect is very weak. An overall rise in yield response is seen after the

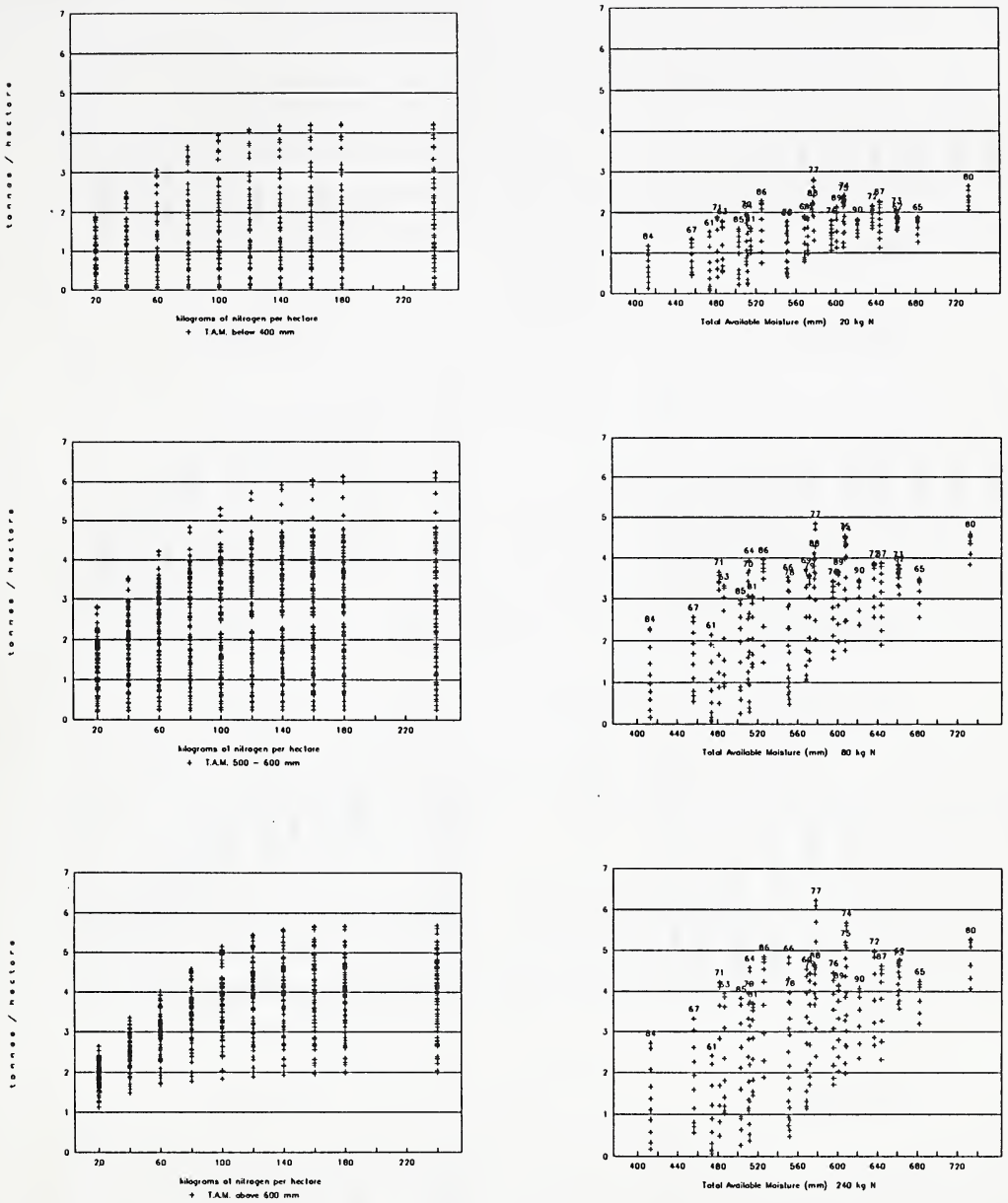
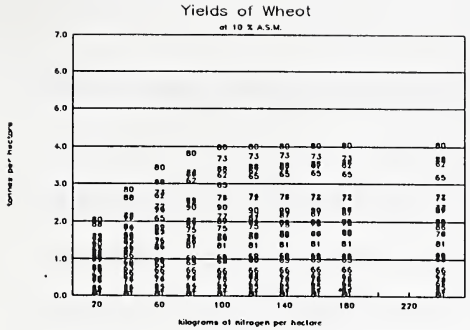
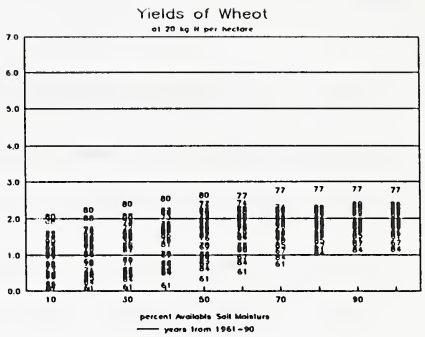
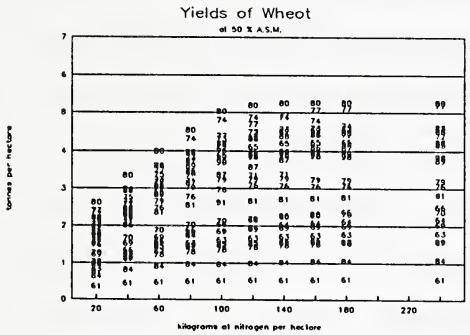

tonnes / hectare
kilograms of nitrogen per hectare
+ T.A.M. below 400 mm
Total Available Moisture (mm) 20 kg N
+ T.A.M. 500 – 600 mm
Total Available Moisture (mm) 80 kg N
+ T.A.M. above 600 mm
Total Available Moisture (mm) 240 kg N

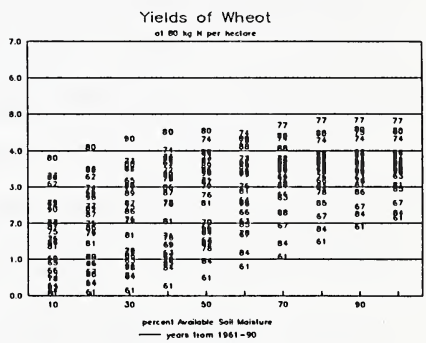
Fig. 5 Wheat yields in tonnes per hectare for ten levels of nitrogen fertilizer application. A=low (Q1), B=medium (Q2), C=high (Q3) total available moisture respectively.

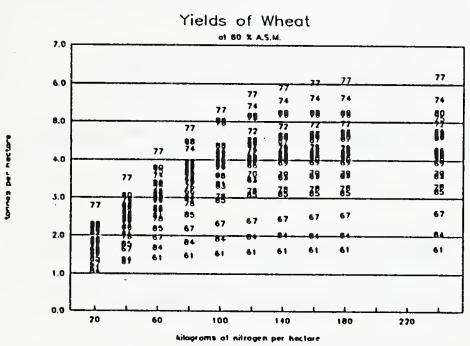
Fig. 6 Wheat yields in tonnes per hectare for 27 years of Ellerslie weather data at A=20, B=80, and C=240 kg N ha^{-1} , representing total available moisture from 400 mm to 740 mm. Numbers in graph indicate years from 1961 -1990.

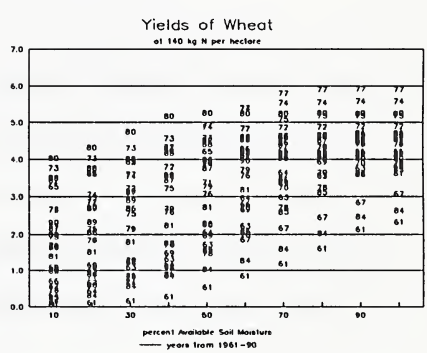


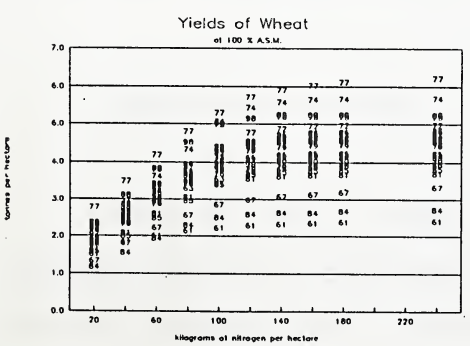












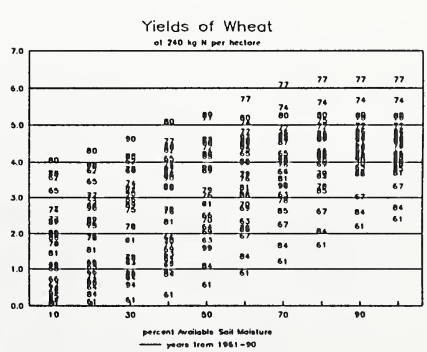


Fig. 7 Yields of wheat in tonnes per hectare for ten levels of nitrogen fertilizer application at four levels of available spring soil moisture, 10% (top), 50 %, 80%, and 100% AvSpSM (bottom).

Fig. 8 Yields of wheat in tonnes per hectare for ten levels of avaiable spring soil moisture (% vol), at four levels of nitrogen fertilizer application rates, 20 kg (top), 80 kg, 140 kg and 240 kgN ha^{-1}. Numbers indicate years from 1961 - 1990.

560 mm total available moisture range. Figure 6 shows the diversity of yield responses when T.A.M. is compared to yield for each year over three different applied nitrogen regimes (20, 80, 240 kg N ha^{-1}). The individual data points indicate the yield for the ten initial starting moisture contents for each year as initialized in the CERES-Wheat model. The crop response again varies dramatically with the year but generally follows a linear to weak quadratic form. Approximately 2100 kg of wheat was produced for every 100 mm of T.A.M. at the 240 kg N ha^{-1} rate. Two tonnes and one tonne were produced at the 80 and 20 kg N ha^{-1} rates respectively for the same amount of total available moisture. Henry (*et al*, 1986) summarize hard red spring wheat yields rising 1000 kg ha^{-1} per 100 mm of water use in Western Canadian studies. The CERES-Wheat consumptive use patterns were approximately double that at higher applied nitrogen rates.

With respect to percent available soil moisture (Fig 8) a more linear spread of the multi-year data from 10 % - 100 % occurred at the 20 kg N ha^{-1} rate. Patterns for the 80 kg N ha^{-1} rate were varied for individual years but could be considered largely linear. At higher rates of Nitrogen application the yield response to available spring soil moisture approached the plateau features of the NRATE graphs.(Figs 5 and 7)

Results of the Validation

Actual field data of yearly initial nitrogen and available spring soil moistures were not available for a true validation of the predicted output. However, observed yields for Katepwa and its parent crop Neepawa were plotted on the predicted output yield ranges of Figure 9 to show the data fit.

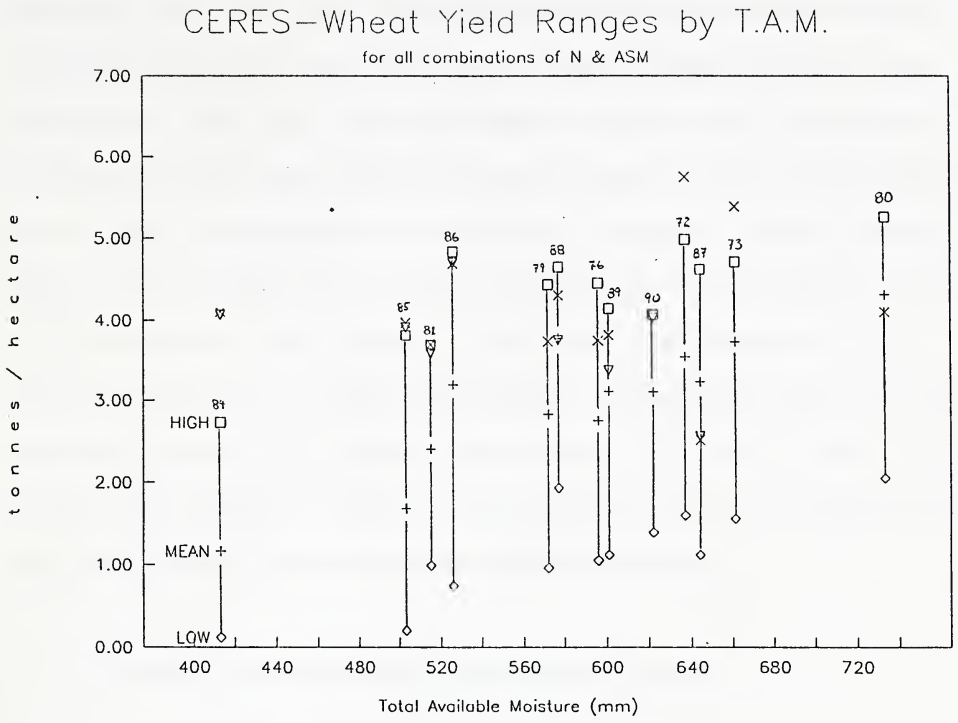


Fig.9 Observed yields for Katepwa (Δ) and Neepawa (X) compared to predicted yields from the CERES-Wheat model for 12 years (#) used in the validation. The range of predicted yields for all combinations of NRATE and % A.S.M. are indicated with a vertical line for each year. High (□), Arithmetic Mean (+), and Low (◊) predicted yields.

The years 1972, 1973, and 1984 were under predicted while the remaining nine years fell somewhere within the range of CERES-Wheat predicted yields. The years 1981, 1985, and 1986 were close to being under predicted while the remaining six years were within the predicted range for that year. The calibration year (1990) is only added for comparison in Figure 9. Without knowing the actual nitrogen levels and available soil moistures it is very difficult to comment on the reliability of the predicted vs. observed yield comparisons with a high level of confidence. A better actual applied nitrogen and spring soil moisture data set would be very valuable in this instance. The years for which observed values were selected in Figure 9 covered the full range of predicted available soil moistures and observed growing season precipitation.

Results of the Stochastic Dominance Testing

When the price of wheat was kept at \$100 tonne^{-1}, nitrogen fertilizer price at \$ 0.36 kg^{-1}, and NRATE ranged from 20 to 240 kg N ha^{-1} over 55 kg intervals, 4 of the 125 strategies were second degree stochastically dominant. These were strategies (333),(334),(343), & (344) which corresponded to 130 kg N ha^{-1} for "A_3" and 185 kg N ha^{-1} for "A_4" (e.g. 343 = 130:180:130 kg N ha^{-1}). This was interpreted to mean when available spring soil moisture was poor: good: to excellent apply nitrogen fertilizer at the corresponding rate combinations of 130 and 185 kg N ha^{-1} over the long run. These strategies concentrated around the curve of the EV frontier representing the highest mean values of gross margin (\$ 107 - \$ 305 ha^{-1}) and medium risk as measured by the standard deviation (\$ 60 - \$ 130 ha^{-1}). By narrowing the range to 100 - 180 kg N ha^{-1} using 20 kg N ha^{-1} increments the second degree stochastically dominant strategies were increased to seventeen ranging from 120:120:120 to

160:160:160 kg N ha^{-1} (i.e. strategy (222) to strategy (444)) under poor: good: and excellent available spring soil moisture conditions respectively. This represented a narrower band width of gross margins ($ 293 - $ 305 ha^{-1}) and standard deviations ($ 90 - $ 102 ha^{-1}).

Further reduction of the NRATE spreading from 110 to 158 kg N ha^{-1} at 12 kg intervals did not lead to any additional narrowing of the gross margin spread nor that of the standard deviation. Twenty three strategies were S.D.S.D. this time from 122:122:122 to 146:158:158 kg N ha^{-1} (i.e. strategies 222 and 455). This would seem to indicate that 146 kg N ha^{-1} would be about the maximum nitrogen that a risk averse producer would apply under any available spring soil moisture conditions and still maintain a probability of doing best economically for the long term. When spring soil moisture conditions were better than 60 % (vol.) in the profile he could consider 158 kg N ha^{-1} and still optimize his gross returns.

The method to follow when using this model would be to start with an applied nitrogen rate that covered the spread for which the embedded production function was specified and do a run. The five nitrogen rates would cover the strategies from (111) to (555) for the three levels of spring soil moisture (Z_n). Identify the nitrogen applications that corresponded to the A_n values of #2 and #4 and do another run of the model making the minimum and the maximum application rates slightly smaller and slightly larger than the previous #2 and #4 rates. Continue to do this until the application rates of # 1 and # 5 start showing in the second degree stochastically dominant strategies. These final spreads would represent the range of application rates a risk adverse wheat producer could apply to optimize his gross margin returns over

the long run. Depending on his level of risk aversion he would apply the lower A_n value in dry springs and the higher A_n application rate in those years where spring soil moisture was above 80 % (vol.) in the profile.

An EV analysis of the 125 strategies showed a distribution of gross margins by standard deviation data points as seen in Figures 10 and 11. As the wheat price rose so also did the mean gross margins and the standard deviations in a roughly linear pattern from lower left to upper right (Fig. 10). Generally as wheat price rose and nitrogen price remained constant the expected gross margins and the associated standard deviations rose as well. This rise in standard deviations was unexpected and cannot be explained at this time. The variation in the fertilizer price variable from \$0.0 kg^{-1} to \$1.45 kg^{-1} showed a pivotal shift from upward right oriented to upward left oriented E.V. strategies all anchored around the strategy (111) (see Fig. 11). Standard deviation ranged from \$ 60 to \$ 150 ha^{-1} and across a wide range of gross margin means (\$ 5 to \$ 368 ha^{-1}). As the nitrogen price increased under a constant wheat price a negative shift in expected gross margins was witnessed as expected.

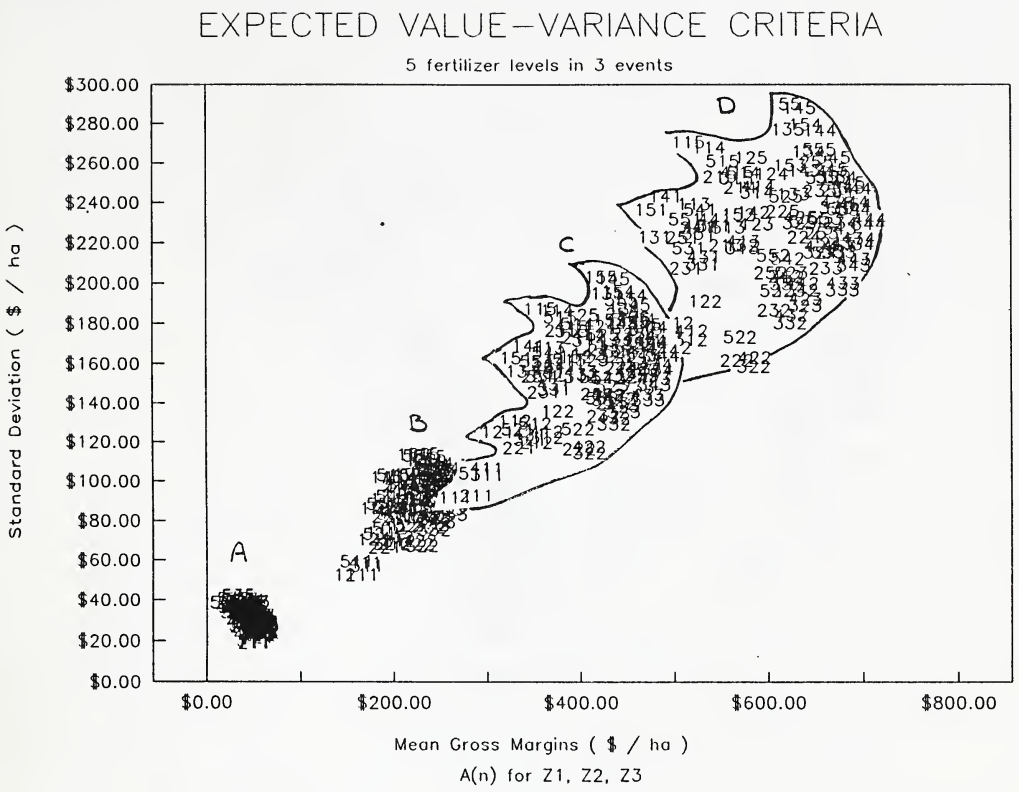


Fig. 10 Grouped fertilizer strategies plotted against Mean Gross Margins and their standard deviations ($ ha^{-1}) at four levels of wheat price (A=$30 B=$90, C=$150, & D=$210 per tonne) and constant fertilizer N price ($ 0.36 kg^{-1})

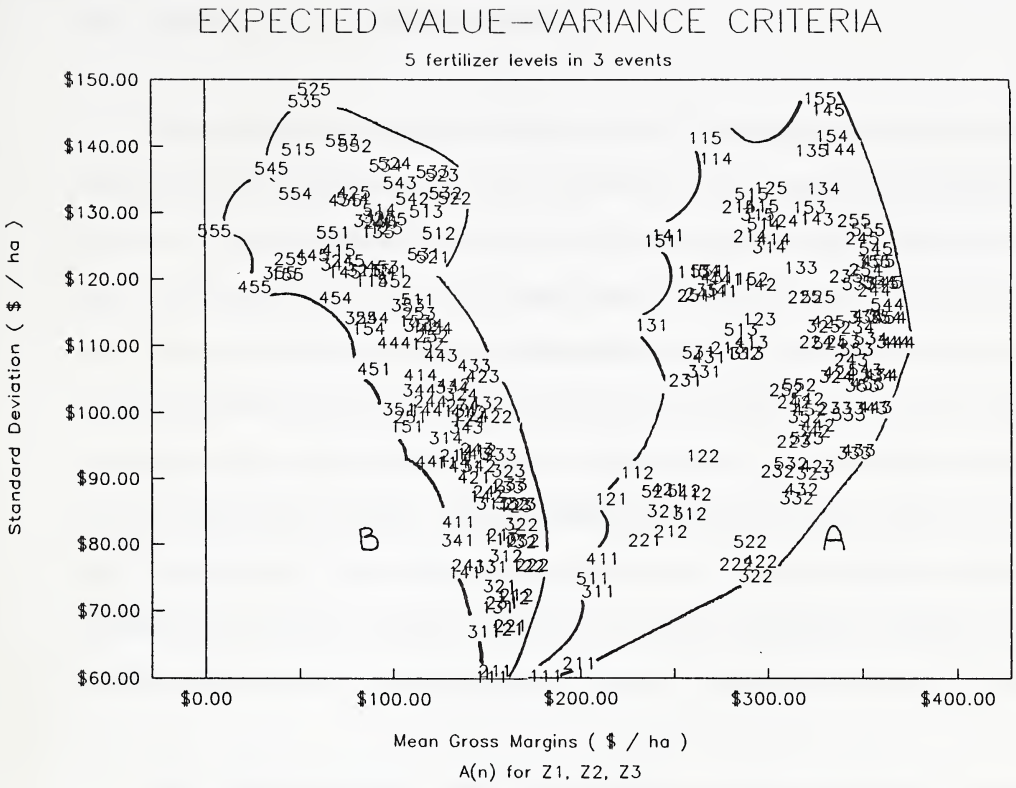


Fig. 11 Grouped fertilizer strategies plotted against Mean Gross Margins and their standard deviations ($ ha^{-1}) at two levels of fertilizer price (A=$ 0.0 kg^{-1} and B=$1.45 kg^{-1}) for a constant wheat price of $100 tonne^{-1}

VI) SUMMARY AND CONCLUSIONS

This project undertook to bring the use of a biophysical model (CERES-Wheat) into the realm of primary data collection for the estimation of production functions. The independent variables of nitrogen fertilizer application rate and water available to the wheat plant were analyzed for their effect on total grain yield. The result of this analysis was the estimation of quadratic and square root production coefficients to best approximate yield response to twenty-seven years of weather data, and soil and agronomic information from the black soil zone south of Edmonton, Alberta. These production functions were used in a Lotus 1-2-3 spreadsheet model calculating the first and second degree stochastic dominance of nitrogen fertilizer application strategies given the variable nature of stored soil moisture and precipitation as random inputs in the growth of wheat.

The CERES-Wheat, daily incrementing simulation program required extensive data input of soil profile characteristics, management practices, and daily weather data for the site being analyzed. Once initialized, the model was calibrated against known (1990) local field data. Input files were created to run a complete factorial design of ten nitrogen rates by ten available spring moisture levels. The yields, growth characteristics, and climatic data for 27 of the 30 years that were successfully simulated by the model were arranged in an ASCII text file to be read as input into commonly available statistical analysis programs and spreadsheets. The data should be regenerated to include the years 1968, 1982 and 1983 that did not function properly in the first simulation run. As well, minor assumptions in initialization factors could be fine tuned to reflect reality at the site more accurately. A complete validation was impossible because of a lack of known initial data from the physical site for any appreciable number of

years. A partial validity check was carried out comparing twelve years of yield data available from the Ellerslie research site with predicted yields for the entire range of spring soil moisture and nitrogen application rates.

Spring soil moisture data collection would be a valuable asset to fertilizer studies in crop production so biophysical models such as these could be initialized and calibrated for various sites around the prairies. Detailed soil profile data are generally lacking in areas of the prairies mapped more than twenty years ago. New soil surveys should take this into account when future mapping is done. Weather data is well documented, however input time could be saved if global solar radiation measures were more available over a wider range of sites. Estimation of this measure from daily bright sunshine hours is laborious and subject to errors in correlation. Further studies in this relationship could be done to improve model input. A stochastic weather generating algorithm would also be valuable for the application of the biophysical model in any locality.

For production function estimation this data set was valuable in that it gave a wider time series with which to work than what was available in the literature. Using all the variables generated from the simulation model, (days to maturity, rainfall to maturity, cumulative evapotranspiration, etc.) estimation of a production function could be done to 80% of explained variability. The inclusion of all these variables was not practical for the final step of the project, but could possibly be used in other yield prediction models. The variables chosen for the production function used in the stochastic dominance model (Nitrogen Rate and Total Available Moisture) were able to explain 68.5% - 71.4% of the variability in yields over these 27 years. This was comparable to many empirical findings in

yield response to nitrogen and water which supports the usefulness of such models in data generation for other sites. Assuming the simulation model accurately predicts yields it does have usefulness in analysis of the yearly variability in yields due to the stochastic nature of the weather. Grimm (*et al*, 1987) suggest that polynomial functional forms such as the quadratic and square root used in this project may tend to over estimate the optimal input levels. Non-linear functional forms such as the Mitscherlich-Baule, hyperbolic, and Von Liebig should be investigated to look at the obvious plateau effect seen in the data set generated by the CERES-Wheat model.

First and second degree stochastic dominance tests were done on an enlarged version of a Lotus 1-2-3 spreadsheet model developed by Bauer (1988). It was able to handle 125 strategies of nitrogen application rates given the probability of three levels of spring soil moisture jointly occurring with three levels of total available moisture for the growing season. The quadratic production function was set into the spreadsheet so that it could calculate gross margin payoffs of wheat with respect to fertilizer costs. User interactiveness was a key feature of the spreadsheet so that input levels of nitrogen, wheat price and nitrogen price could be changed to see the effect on dominant strategies. Any production function that used nitrogen rates and total available moisture as independent variables could be easily inserted into the spreadsheet to measure their responses to stochastic dominance tests. Dominant sets of strategies were calculated and found to cluster around the high gross margin payoffs and medium standard deviation ranges along an EV frontier.

Strategies that applied between 122 and 158 kg N ha^{-1} optimized wheat production gross margins over the long run. A user would still have to rely

somewhat on his own subjective judgment of the field conditions at and just after seeding to determine the final amount of nitrogen he would apply to his wheat crop.

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APPENDIX

STATES OF NATURE

(⚑ Denotes CERES filenames)

File #1. Daily Weather Data

(⚑	ELUA0199.W91	1961-1990	30 years
⚑	ELUA0112.W??	19??-	12 months
⚑	ELAU0124.W??	19??-	24 months)

Solar radiation, minimum and maximum temperatures, and precipitation from the Edmonton International Airport for the 30 years between 1961-90, were obtained from Alberta Agriculture, Resources and Conservation Branch and Environment Canada, Climatological Services. Solar radiation in MJ m^{-2} were calculated from total bright sunshine hours through the Milankovitch equation (List, 1966) and the following regression (Selirio, 1970)

(17) $Qb = Qo\ (0.251 + 0.616\ (n/N)) * 0.041855$

where Qb = daily global solar radiation (MJ m^{-2})
Qo = daily solar radiation (top of the atmosphere (Langleys))
n = daily bright sunshine (hours)
N = total possible daylight (hours)

The coefficients $\alpha = 0.251$ and $\beta = 0.616$ range in value in the literature. Other values recorded were $\alpha = 0.18 - 0.31$ and $\beta = 0.49 - 0.64$. They are dependent on thickness of the atmosphere (i.e. altitude) over the test site, concentrations of absorbing and scattering particles (i.e. CO_2, H_2O, and O_3). Variations in recorders, card types, and measurement techniques can affect the total bright sunshine hours coefficient.

Amplitude of annual temperature variation and annual average ambient temperature were also calculated from the climatological data. Daily weather for one growing season or several concurrent years can be input to test the wheat response to a different climate (see filename = ELUA0199.W91). The question arises as to whether one can synthesize an average, a good, or a poor year either randomly through the computer or statistically from known probabilities.

File #4. Soil Nitrogen Balance Parameters (ELUA9202.WH4)

Organic Matter Returned: ..... 3000 kg ha^{-1}
Depth of Incorporation: ..... 15 cm
C : N Ratio: 80:1
Root Matter: ..... 300 kg ha^{-1}

File #5. Soil Profile Properties by Layer (SPROFILE.WH9)

	Layer Depth (cm)	Lower Limit (m^3 m^{-3})	Upper Limit (m^3 m^{-3})	Bulk Density (Mg m^{-3})	pH
Layer 1	0 - 10	0.165	0.275	0.91	6.9
Layer 2	10 - 20	0.215	0.359	1.19	6.9
Layer 3	20 - 40	0.190	0.324	1.30	6.9
Layer 4	40 - 60	0.207	0.335	1.50	6.8
Layer 5	60 - 80	0.201	0.350	1.50	6.7
Layer 6	80 -120	0.212	0.384	1.50	7.1
Layer 7	120 -160	0.212	0.384	1.50	7.0

File #6. Soil Profile Initial Conditions (ELAU9202.WH5)

Available soil water: ..... 10% intervals from 10 to 100% (vol)

Total Ammonium
and Nitrate levels: ..... 51 kg ha^{-1} (whole profile)

	Layer Depth (cm)	Initial Limit (m^3 m^{-3})	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})
Layer 1	0 - 10		1.0	4.0
Layer 2	10 - 20	varied	1.0	3.1
Layer 3	20 - 40	from	1.0	1.3
Layer 4	40 - 60	10% - 100%	1.0	1.1
Layer 5	60 - 80	of	1.0	1.0
Layer 6	80 -120	Upper	1.0	1.0
Layer 7	120 -160	Limit	1.0	0.9

DECISION VARIABLES

File #2. Genetic Coefficients (GENETICS.WH9)

Physiological parameter	Coefficient for Katepwa	Use in the Model
a) vernalization	P1V = 0.0	required # of vernalization days
b) photoperiodism	P1D = 1.0	rate at which terminal spikelet develops
c) grain filling duration	P5 = 2.3	# of days from anthesis to physiological maturity
d) kernel number	G1 = 2.6	# kernels per gram of stem and spike at anthesis
e) kernel filling rate	G2 = 1.5	mg/day under optimum conditions
f) spike number	G3 = 4.5	dry weight of stem and spike at end of jointing

Phyllochron Interval = 95 Degrees Thermal Time (DTT) $leaf^{-1}$

File #3. Management Data (ELUA9202.WH8)

Start of Simulation: ..... April 15 of each year DOY 105
Date of Seeding: ..... May 10 of each year DOY 130
Rate of Seeding: ..... 300 plants m^{-2}
Depth of Seeding: ..... 5 cm
Row Spacing: ..... 15 cm
Irrigation: ..... none (rain fed)

File #7. Fertilizer Management Data (ELUA9202.WH7)

Date of application: ..... May 1 of each year DOY 121

Rates: ..... 0 - 180 kg N ha^{-1} (in 20 kg increments)
..... and 240 kg N ha^{-1}

Depth of incorporation: ..... 15 cm
Type: ..... Anhydrous Ammonia (82-0-0)

C.1
18322
18322

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THESIS 1993 C.1

RYNING, Kenneth
Stochastic Dominance
Analysis Using a Biophysical
Modelled Crop Production
Function

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